stop and sbottom searches at CMS

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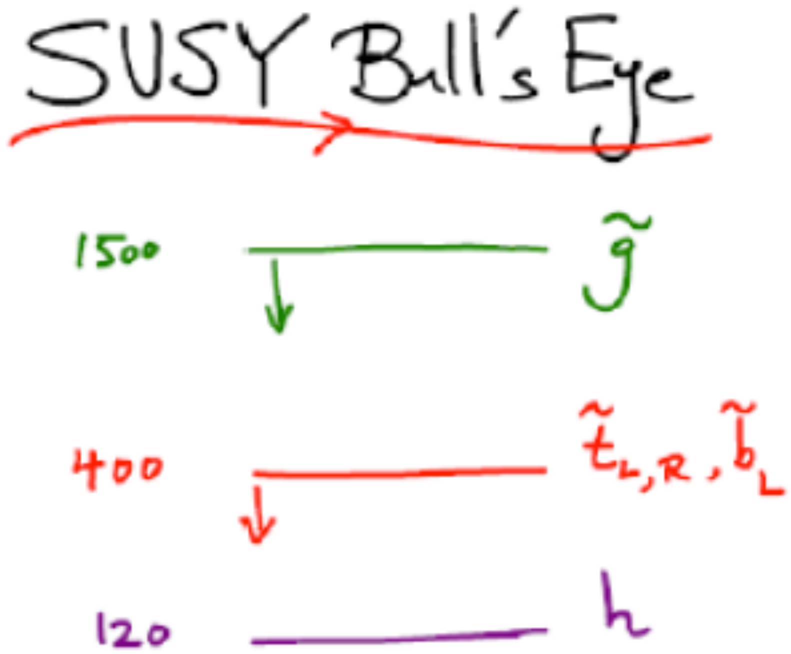
Why 3rd generation

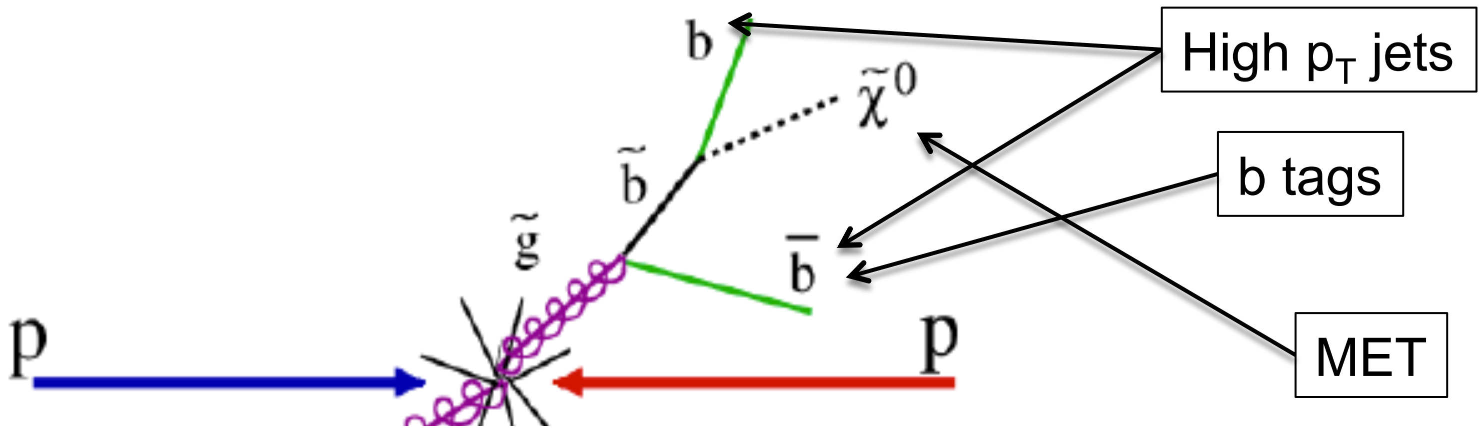


N. Arkani-Hamed
https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=157244

- Naturalness requires (at least) relatively light stops and sbottom
- Without naturalness, SUSY loses lots of its appeal
- The LHC in 2011/2012 is knocking on the door of sensitivity to this crucial region of phase space
- This talk covers current CMS searches for stops and sbottoms and some ideas for the future

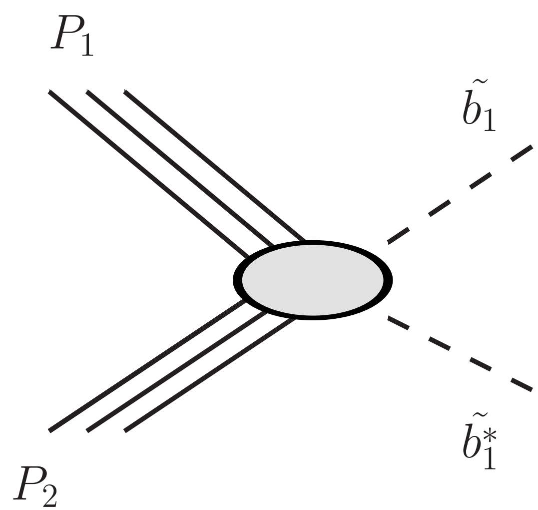
What 3rd gen SUSY looks like

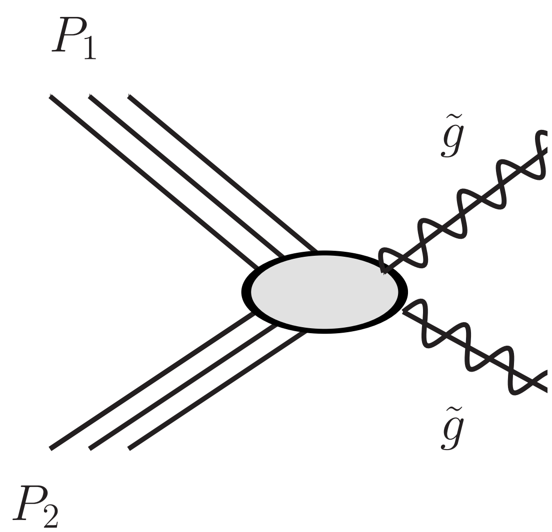
- Experimentally, the only option is to search for final state topologies
  - Doesn't matter what model you think of, you'll measure what you measure
  - Many signatures can capture multiple plausible models
  - Other models may require dedicated searches
- Main unifying string is presence of b jets, which show up eventually in stop and sbottom decays and help reject backgrounds
- General SUSY features of large hadronic activity and missing energy still apply, though so do all of the caveats that come with those assumptions

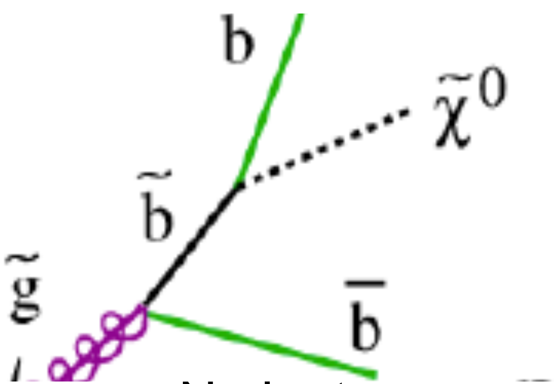


Talk organization

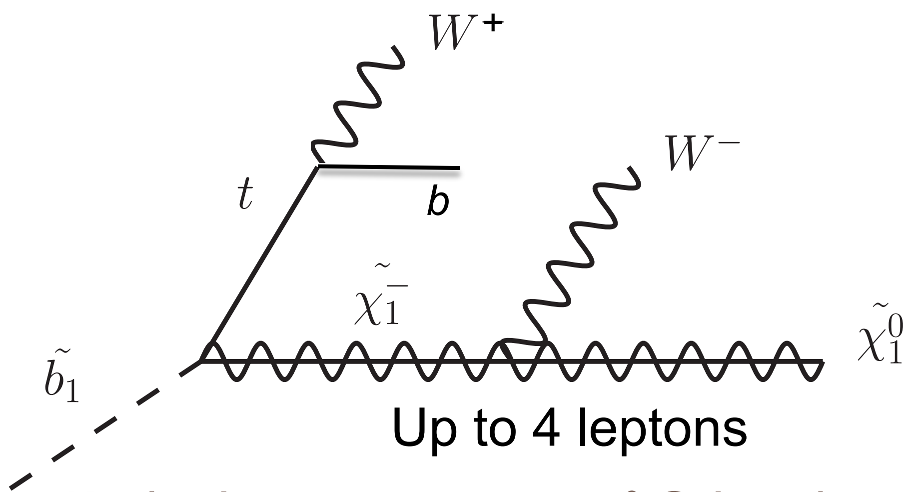
- Consider direct stop and sbottom pair production, but also gluino pair production with decays to stop and sbottom
  - Need a light-ish gluino, too
- Here, I've organized the CMS searches by the number of leptons in the final states moving from 0 to 1 to 2
  - Brand new results today for 0L and 1L!







No leptons

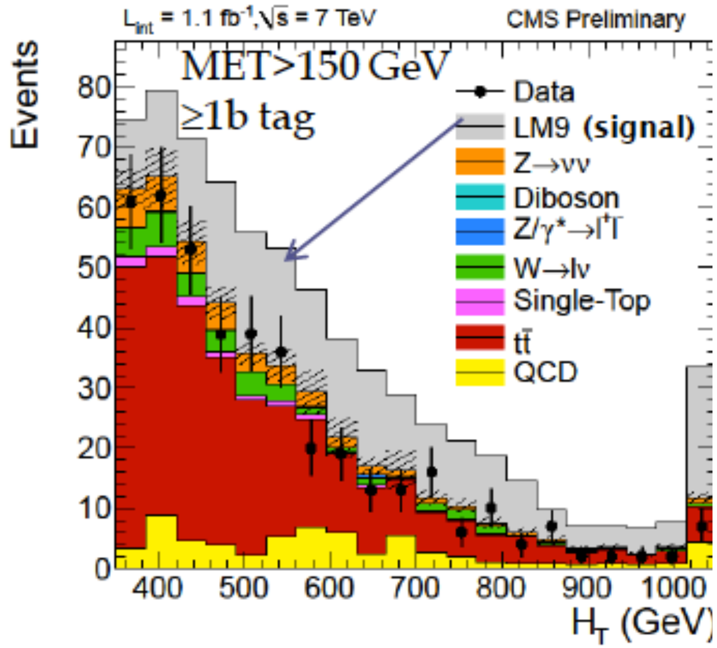


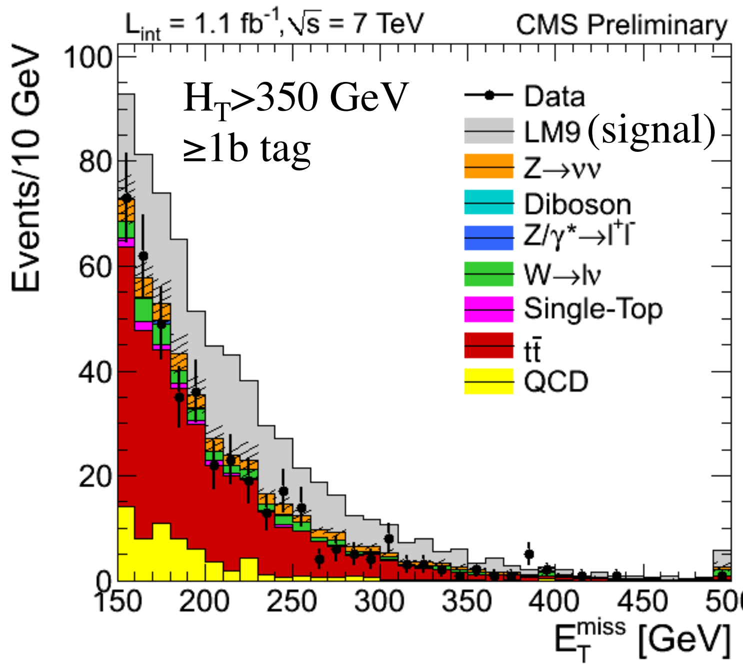
Up to 4 leptons

Classic hadronic search: jets+MET+b

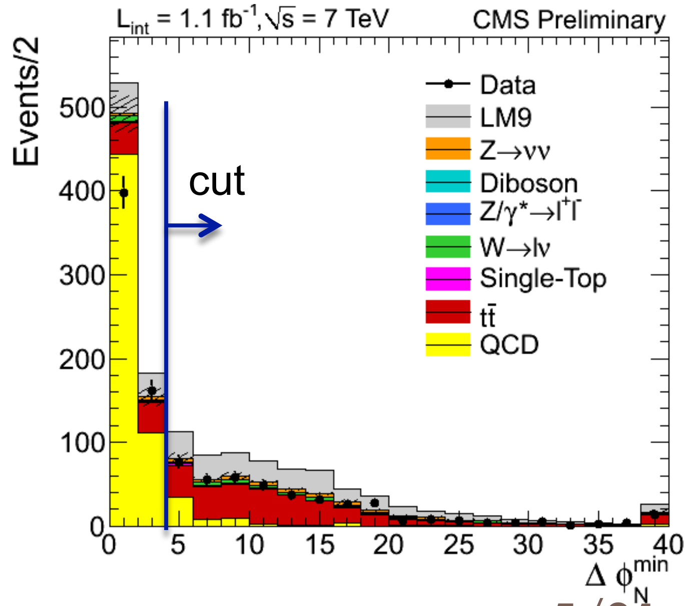
SUS-11-006

- Hadronic activity
  - $\geq$ 3 jets with p_T > 50 GeV
  - $HT = \Sigma_{jets} |p_T|$ > 350 GeV
- Missing energy: MET > 200 GeV



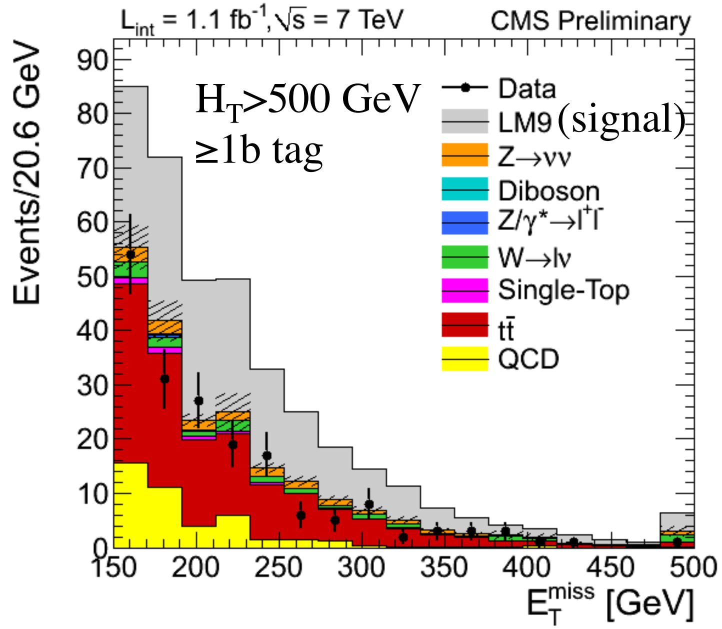


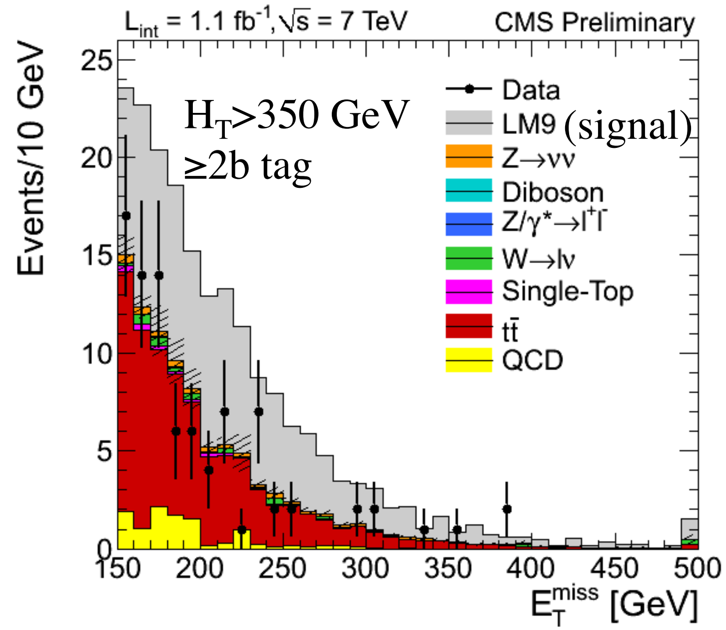
- b jets: $\geq$ 1 tagged jet
  - Reduce all but top backgrounds
- Veto events with an isolated μ^- or e^-
  - Reduce top, W and Z backgrounds
- Minimum azimuthal separation between MET and jets ($\min(\Delta\phi_N)$)
  - Reduce mismeasured multi-jet backgrounds



Jets + MET + b: backgrounds

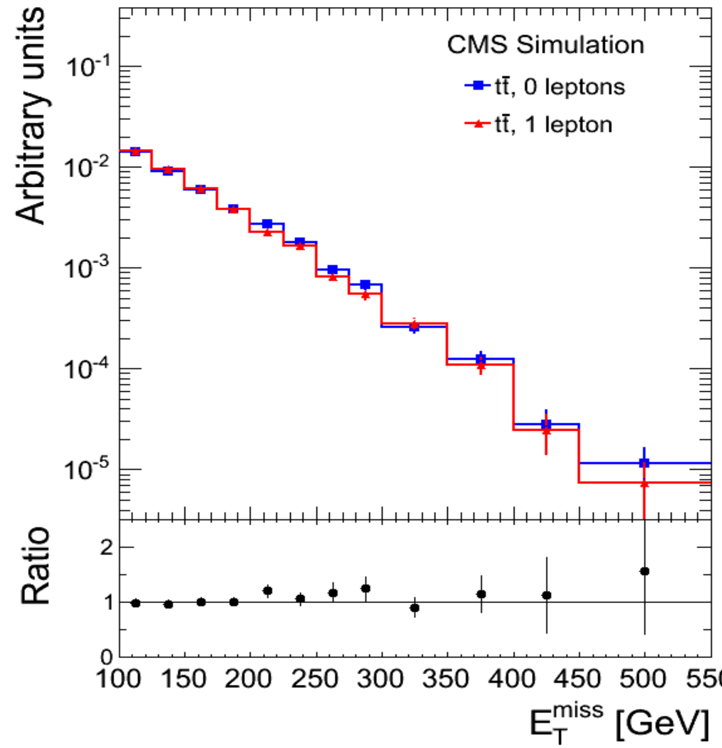
- Remaining backgrounds are dominated by tt events
  - Real MET from W decays, plus real b jets from top decays
  - ≥ 2 b tag region almost all tt
- Smaller contributions from multi-jet QCD, W+jets, Z→νν+jets, and single top
  - Real MET from W, Z decays, or real b jets from top decays
- Data-based measurements of three main backgrounds
  - tt+W+t combined (next slides)
  - QCD: unique approach with resolution-normalized Δϕ(jet,MET) to decorrelate it from MET
  - Z→νν: scaled from $Z \rightarrow l^+l^-$ yields

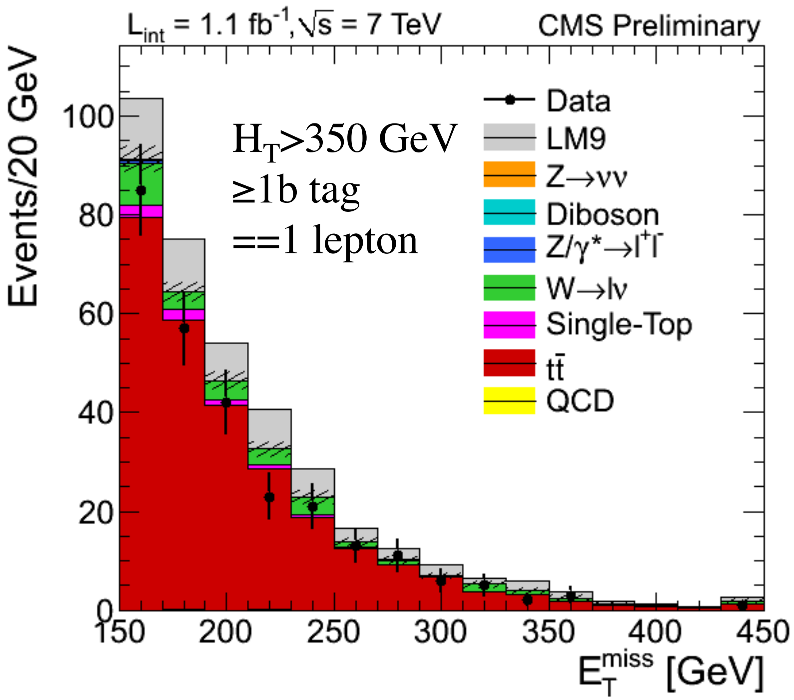




Jets + MET + b: tt+W+t background (I)

- Use single lepton control sample to measure the shape of the MET distribution with all other selection cuts applied
  - Simulation shows MET shape agrees between 0/1 lepton samples

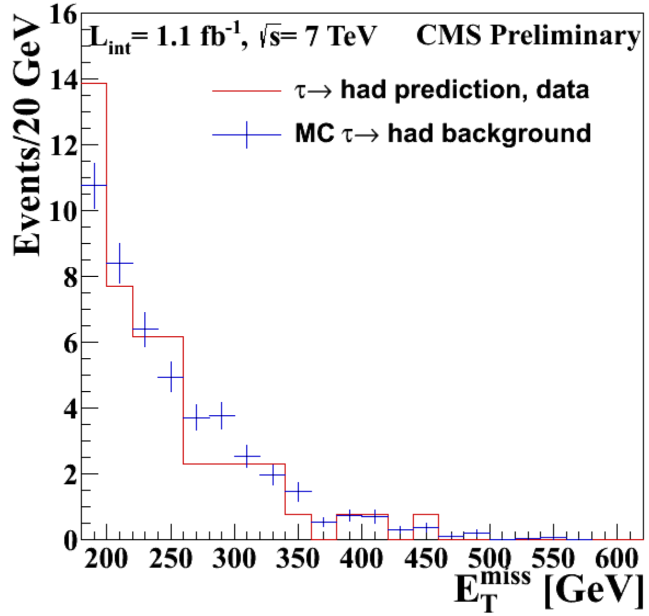


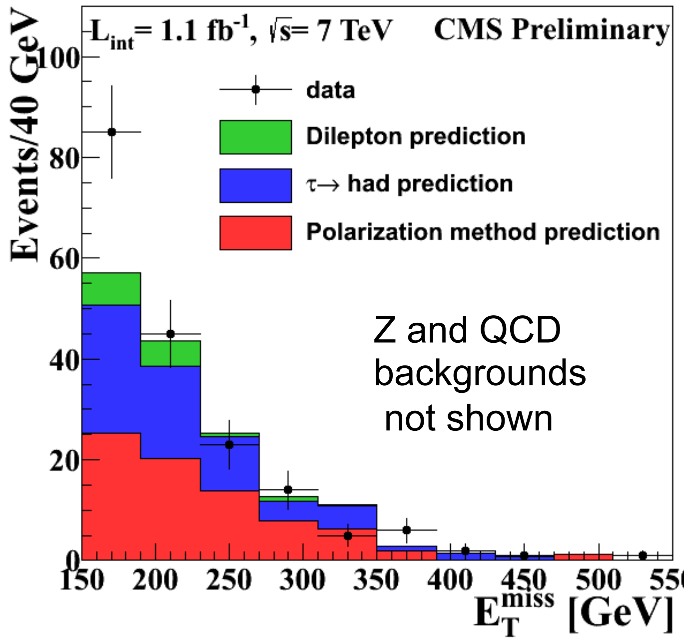


- Normalized 1L MET shape in 0L low MET sideband to predict signal region background
  - Subtract non-tt+W+t contributions based on data-driven estimates

Jets + MET + b: tt+W+t background (II)

- Employ alternative tt+W+t background method based on reweighting single μ control sample MET distribution
- Divide tt+W+t background into categories with 0/1/2 true e or μ
  - 0L events from hadronic tau decays: use single μ control sample and simulate τ response
  - 1L events: Use known correlation between μ p_T and MET due to W polarization to predict MET shape
  - 2L events: Use dilepton control sample for normalization and MET shape from simulation





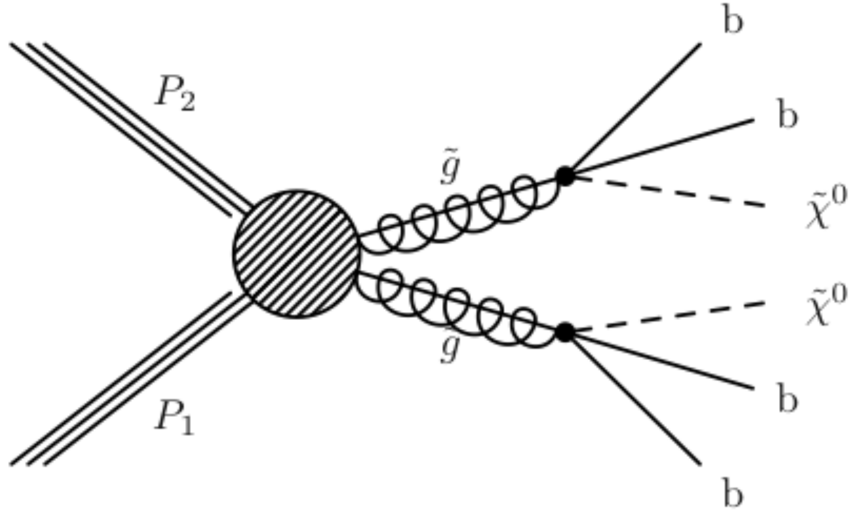
Jets + MET + b: results

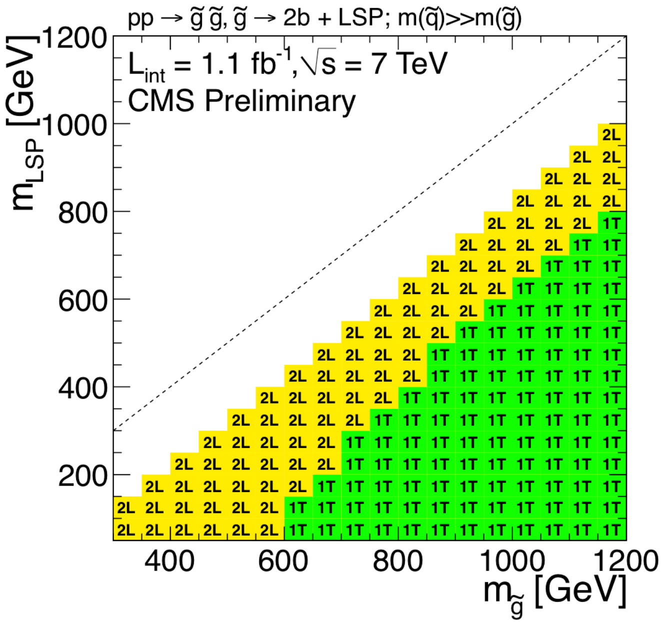
- To increase sensitivity to different kinematics, 4 signal regions are considered
  - $\geq$ 1 or 2 b tags
  - Loose = HT > 350, MET > 200
  - Tight = HT > 500, MET > 300
- Combined likelihood includes all sideband measurements and event counts to properly account for correlations and signal contamination
- No data excess in any search region

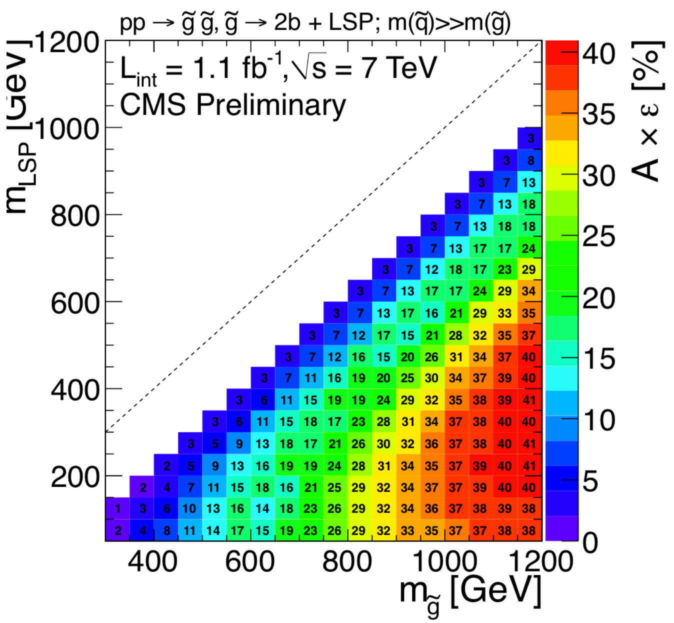
	Loose search region		Tight search region	
	≥ 1 b	≥ 2 b	≥ 1 b	≥ 2 b
QCD	$9 \pm 1 \pm 9$	$0.0 \pm 0.4^{+5.8}_{-0.0}$	$0.2 \pm 0.2^{+0.5}_{-0.2}$	$0.1 \pm 0.1^{+0.4}_{-0.1}$
top and W+jets	$108 \pm 18 \pm 13$	$24 \pm 7 \pm 5$	$13 \pm 5 \pm 4$	$7 \pm 4 \pm 3$
top and W+jets cross-check	—	—	$17.0 \pm 5.7 \pm 2.1$	$5.9 \pm 3.5 \pm 1.3$
$Z \to \nu\bar{\nu}$	$24 \pm 11 \pm 4$	$2.6 \pm 2.9 \pm 2.0$	$5.0 \pm 1.6 \pm 2.0$	$0.2 \pm 0.4 \pm 0.5$
Total SM	$141 \pm 21 \pm 16$	$25.8 \pm 7.4^{+7.8}_{-5.2}$	$18.2 \pm 5.3 \pm 4.5$	$7.3 \pm 4.0 \pm 4.3$
Data	155	30	20	5

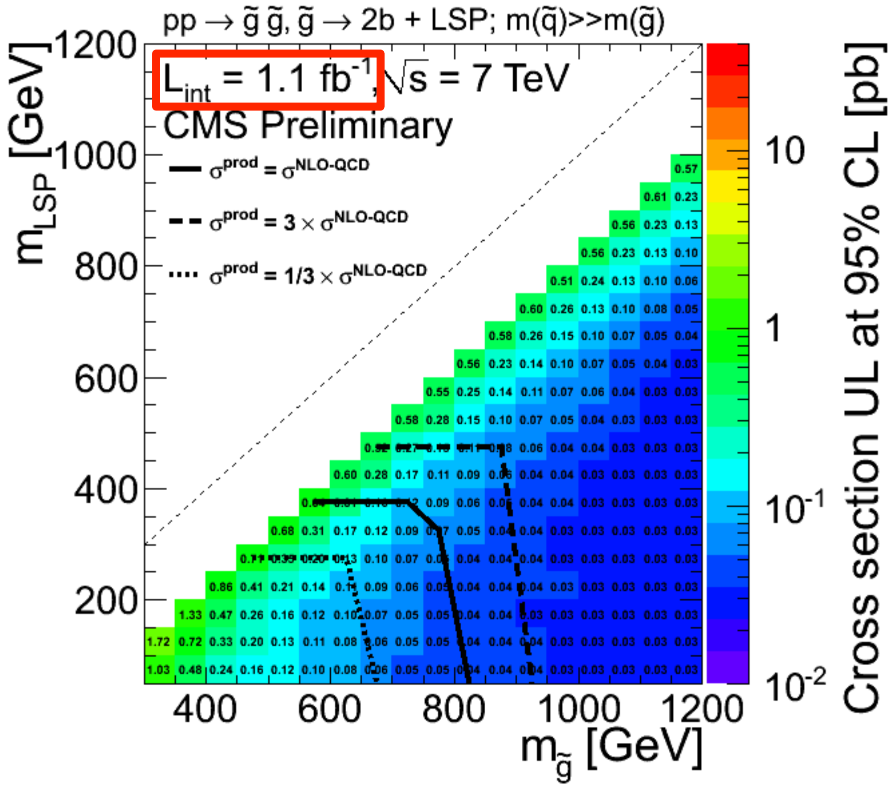
Jets + MET + b: interpretation

- Since no signal, set limits on relevant models
- Prime model "T1bbbb"
- Use result from signal region with best expected sensitivity
  - Tighter kinematic selection does better with larger mass splittings
  - Looser kinematics compensated with tighter nB jet cut
- Gluino masses ~800 GeV excluded for LSP masses up to ~400 GeV in this model







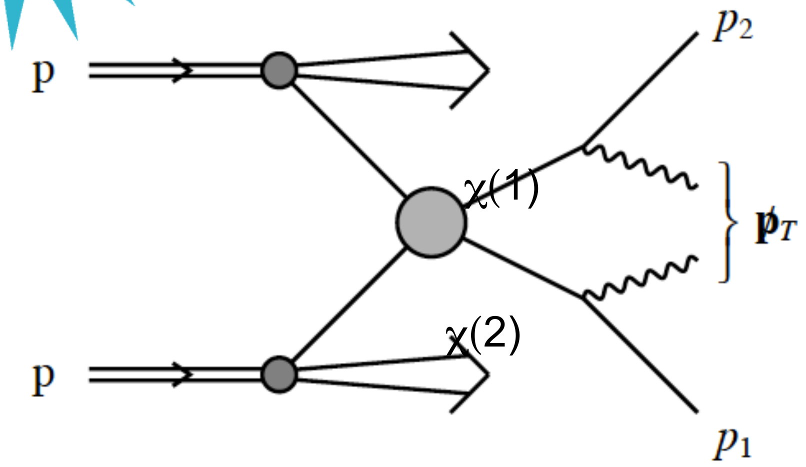


M_{T2} with b jets

New!

SUS-12-002

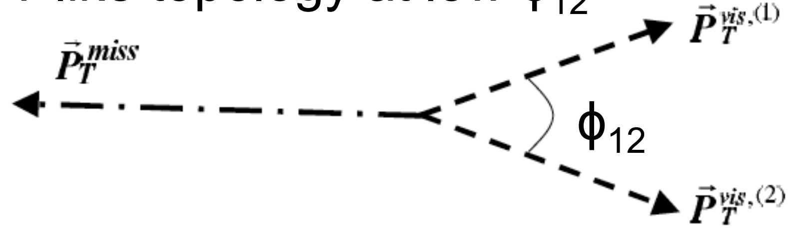
- The M_{T2}-based analysis (described by Kenichi Hatakeyama on Wednesday) is also extended to include a b tagged jet
  - M_{T2} = "stransverse mass" = generalization of M_T to case of two similarly decaying particles with MET
  - For correct m(χ), end point of MT2 is parent particle mass
  - Divide multi-jet events into two "pseudojets"
  - Consider simplified case with massless pseudojets and m(χ) = 0
  - Back-to-back jets, as from QCD events, peak at 0 (even with mismeasured p_T)
  - Parallel jets and large MET (characteristic of many SUSY events) have large M_{T2}



$$M_{T2}(m_\chi) = \min_{p_T^{\chi(1)} + p_T^{\chi(2)} = p_T^{miss}} \left[\max\left(m_T^{(1)}, m_T^{(2)} \right) \right]$$

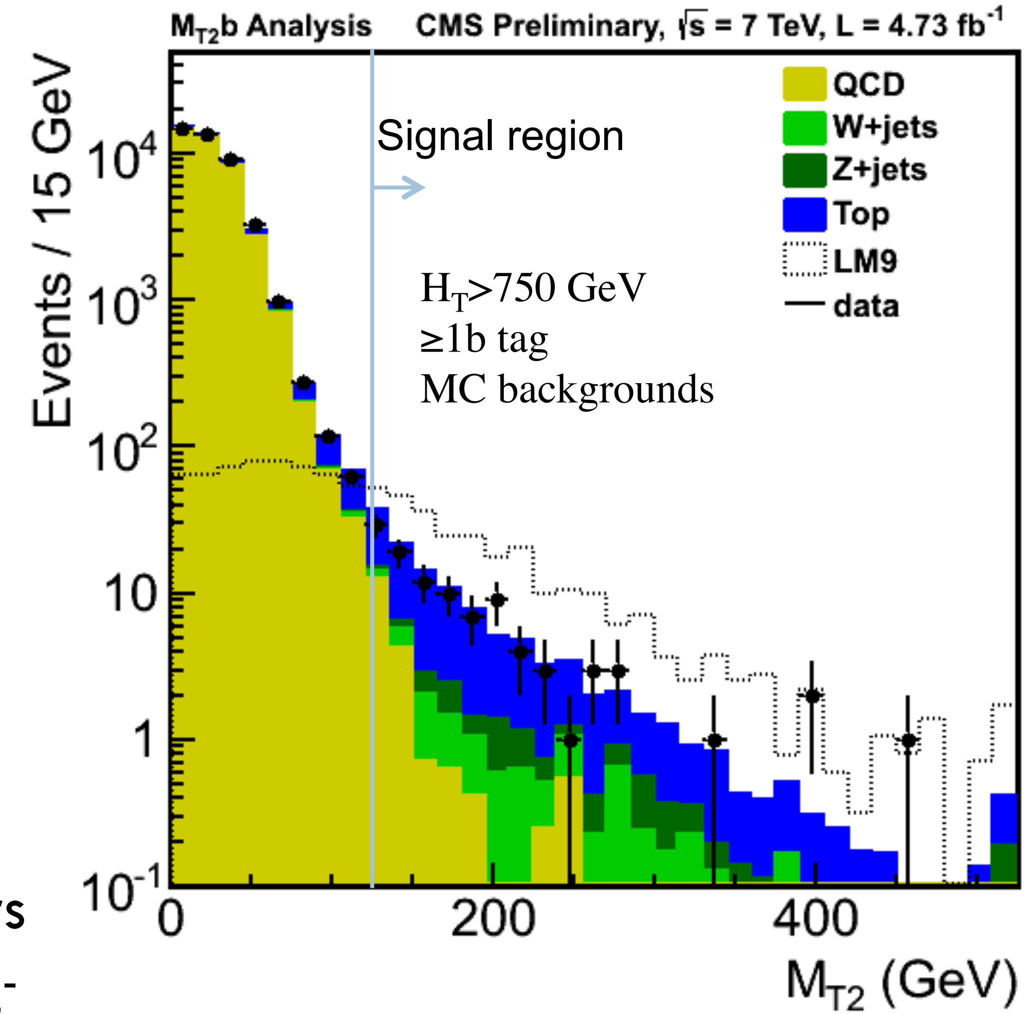
$$(M_{T2})^2 = 2 p_T^{vis(1)} p_T^{vis(2)} (1 + cos\phi_{12})$$

SUSY-like topology at low ϕ_{12}



M_{T2}b: selection

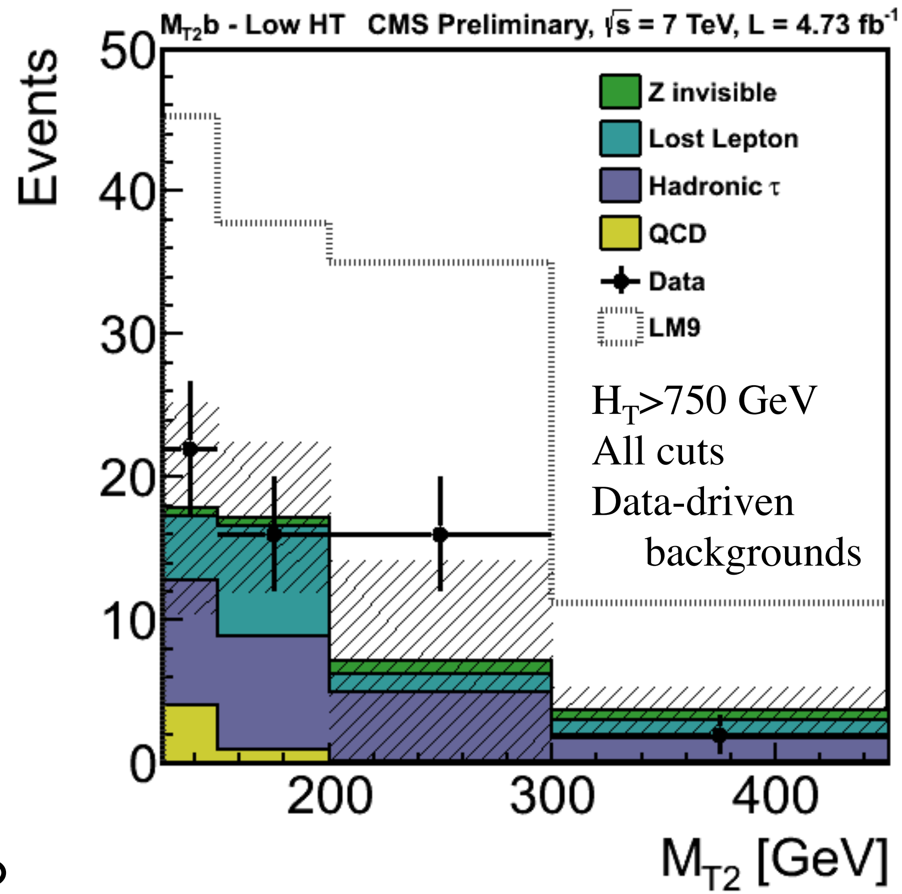
- Require ≥ 1 high-purity b jet
  - ~42% efficiency
  - ~0.1% (6.3%) mistag rate for udsg(c) jets
- Require ≥ 4 jets
  - p_T > 150/40/40/40 GeV
- HT > 750 GeV
- M_{T2} > 125 GeV
- MET > 30 GeV
  - Computed from particle flow algorithm incorporating information from all subdetectors
- Veto events with isolated e^- or μ^-
- $\Delta\phi$(jets, MET) > 0.3



Dominant background from top, with real b jets

M_{T2}b: background estimation

- Backgrounds for M_{T2}b measured in data with same techniques as M_{T2} inclusive
  - tt and W
    - Lost lepton method: count single lepton events in data and scale by probability to lose lepton measured in MC
    - Hadronic τ method: measured in data and corrected by reconstruction and ID efficiency, observed to be consistent with MC
  - QCD
    - Naturally suppressed by M_{T2} cut
    - M_{T2} sideband used to fit for pass/fail ratio in $\Delta\phi_{min}$ and extrapolate to signal region
  - $Z\rightarrow\nu\nu$ measured by counting W + jets events in data passing other selection criteria (except b tag) and scaling by ratio of W/Z production and W reconstruction efficiency



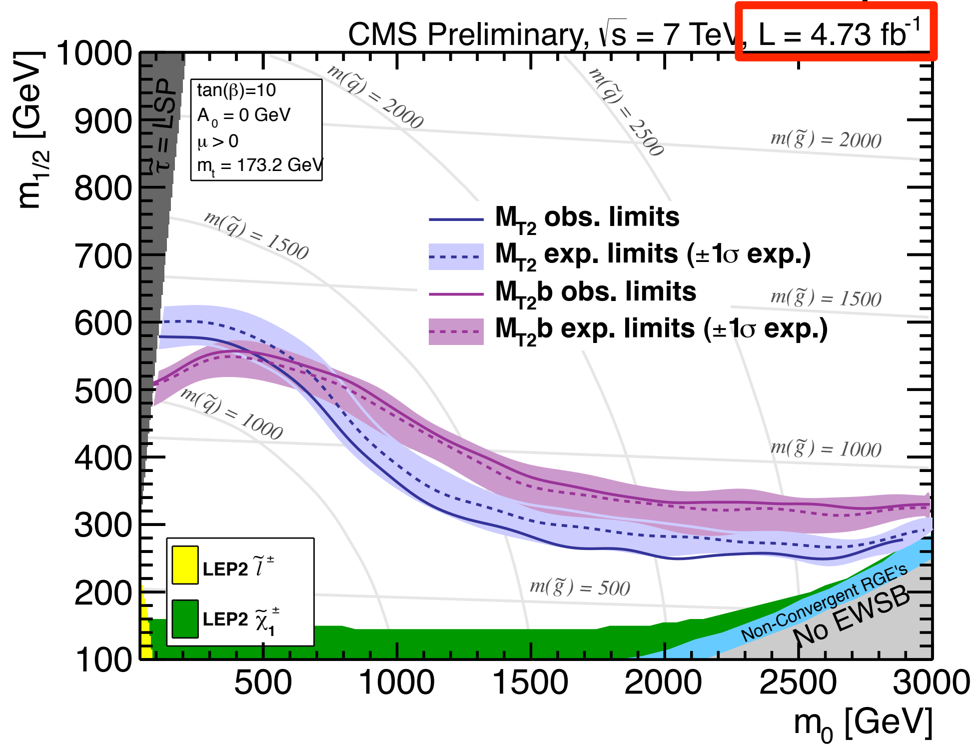
M_{T2}b: results

- Results split into 2 HT bins and 4 M_{T2} bins
  - Measure backgrounds and count data events separately in each
  - All data-driven backgrounds in good agreement with MC expectations
  - Unfortunately, also in good agreement with the data

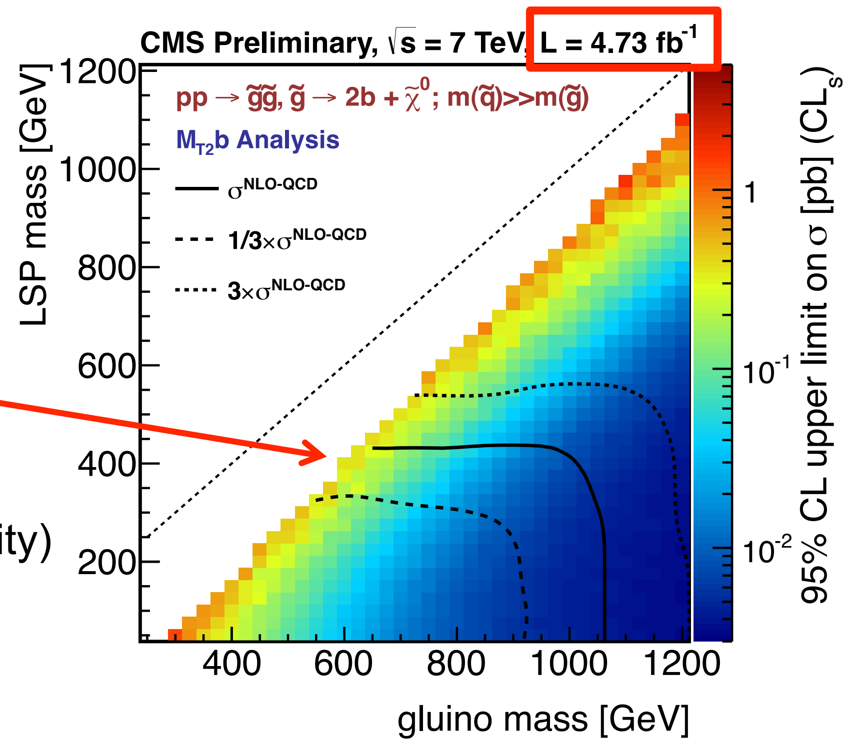
M_{T2} bin	$Z \to \nu\nu$ MC	$Z \to \nu\nu$ data pred.	Lost lepton MC	Lost lepton data pred.	$\tau \to had$ Estimate	QCD MC	QCD data pred.	Total bkg. MC	Total bkg. data pred.	Data
$750 \le H_T \le 950$										
[125,150)	1.0	0.5 ± 0.4	12.8	4.5 ± 3.2	8.7 ± 6.3	5.16	4.1 ± 2.1	28.3	17.8 ± 7.3	22
[150,200)	2.0	0.7 ± 0.3	11.3	7.6 ± 3.6	8.0 ± 3.8	0.16	0.90 ± 0.51	22.1	17.2 ± 5.2	16
[200,300)	1.3	1.0 ± 0.5	6.1	1.3 ± 1.7	4.9 ± 6.7	0.0	0.04 ± 0.03	12.6	7.2 ± 6.9	16
≥ 300	0.5	0.6 ± 0.3	1.3	1.3 ± 0.9	1.8 ± 1.3	0.0	0.00 ± 0.00	3.7	3.7 ± 1.6	2
$H_T \ge 950$										
[125,150)	0.6	0.4 ± 0.3	6.2	5.9 ± 3.3	4.3 ± 2.4	1.25	5.4 ± 2.8	12.7	16.0 ± 4.9	10
[150,180)	0.4	0.9 ± 0.4	4.6	6.4 ± 3.3	3.2 ± 1.7	0.57	1.7 ± 0.9	9.0	12.2 ± 3.9	10
[180,260)	0.6	0.1 ± 0.1	4.2	3.4 ± 2.3	3.3 ± 2.3	0.67	0.45 ± 0.25	9.1	7.2 ± 3.2	9
≥ 260	0.6	0.7 ± 0.4	2.2	2.0 ± 1.6	1.6 ± 1.3	0.04	0.05 ± 0.04	4.6	4.3 ± 2.0	3

M_{T2}b: interpretation

- Simultaneous likelihood fit to all bins uses HT and M_{T2} shape to maximize signal and background discrimination
- Since no signal, extract upper limits on cross sections with CL_S
- CMSSM limits better with M_{T2}b looser M_{T2} cut at high squark/low gluino masses
  - Exclude squark mass up to ~1200 GeV
- Most sensitive here, too, to T1bbbb (gluino-mediated sbottom production)
  - Gluino masses excluded up to ~1 TeV for LSP up to ~400 GeV



Huge improvement over MET+b (~5x luminosity)

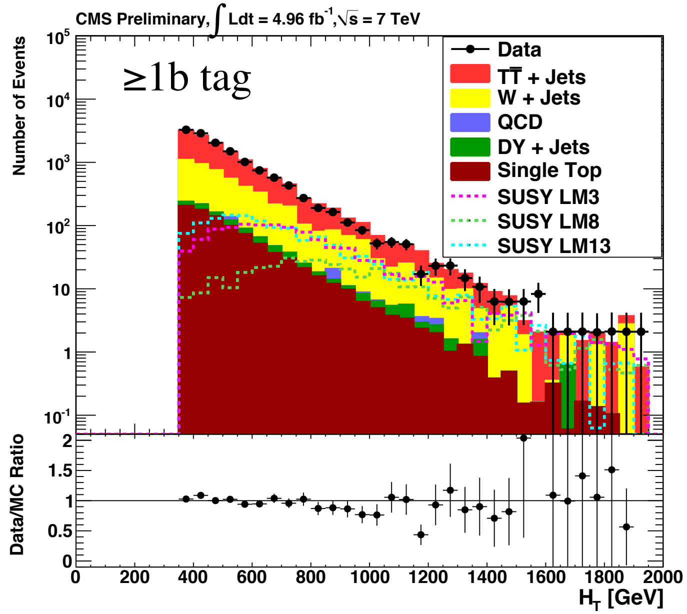


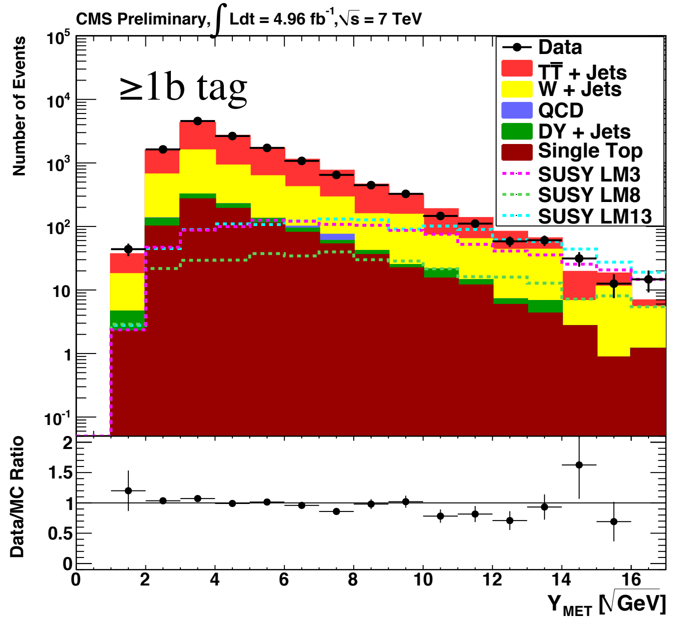
Single lepton + b search

New!

SUS-11-028

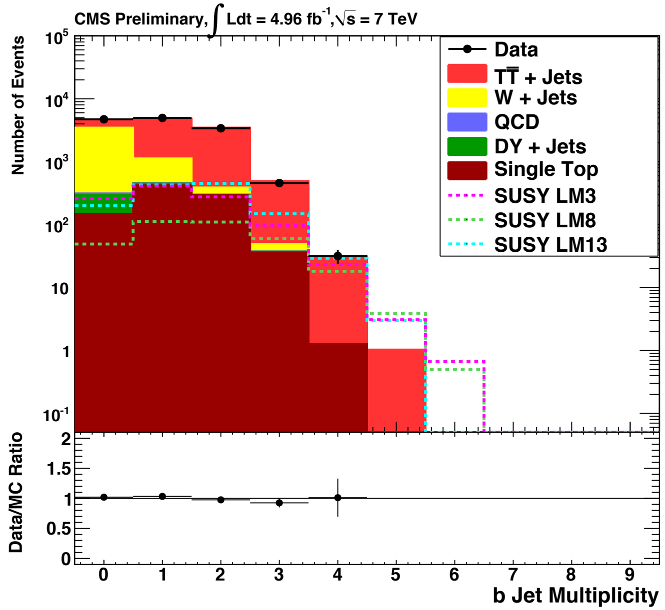
- Extend single lepton + jets search to include b tags
  - $\geq$ 4 jets with p_T > 40 GeV
  - 1, 2 or $\geq$3 b-tagged jets
  - Single isolated e/μ with p_T > 20 GeV
  - Reject events with 2nd lepton
    - Avoid overlap with multi-lepton searches
    - Use looser isolation requirement and p_T > 15 GeV
  - Signal region
    - HT > 650 GeV
    - MET significance, Y = $(MET/\sqrt{HT}) > 5.5$
  - Control region: HT>375, MET>60

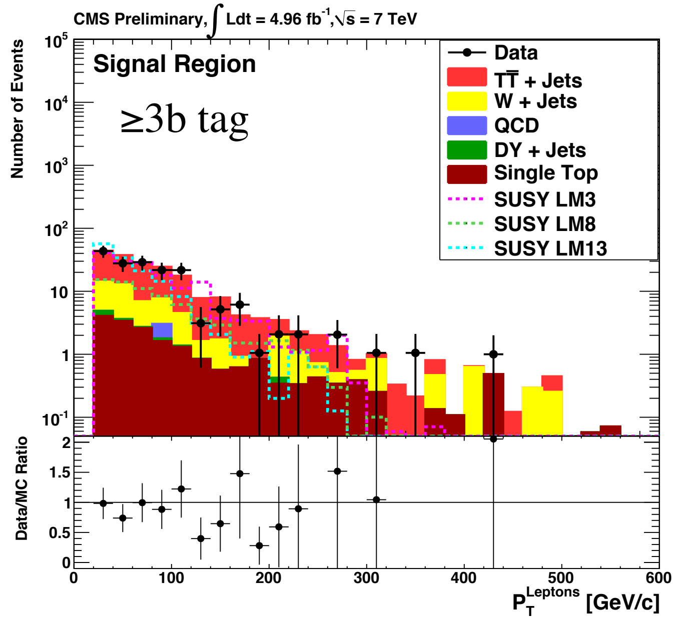




Single lepton + b: b tagging

- Good data/MC agreement in number of b jets
- Top backgrounds dominate with ≥ 2 b jets
- B jet p_T distribution also in good agreement with MC
- p_T spectra not very different between backgrounds (tt, W +jets single top) or benchmark signal points (LM3, 8, 13)



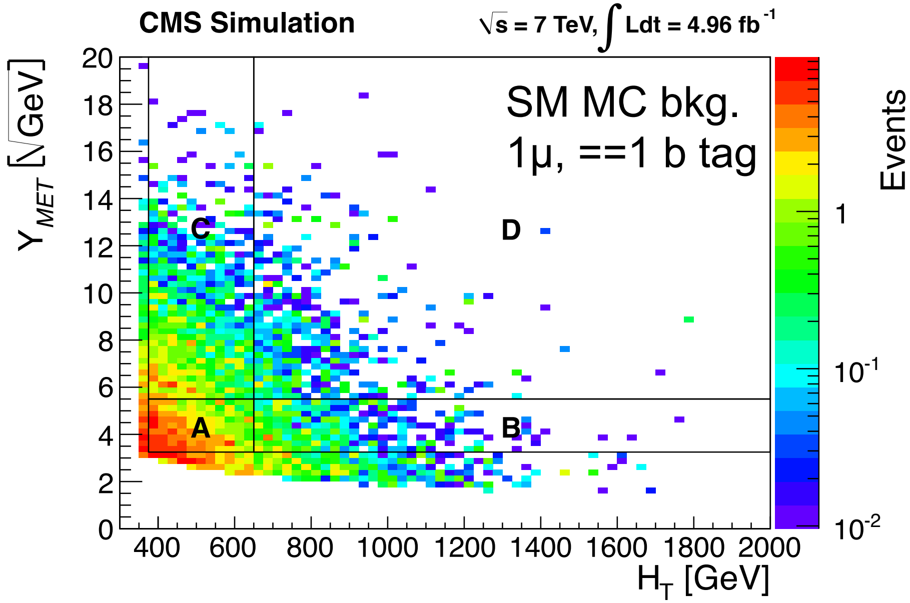


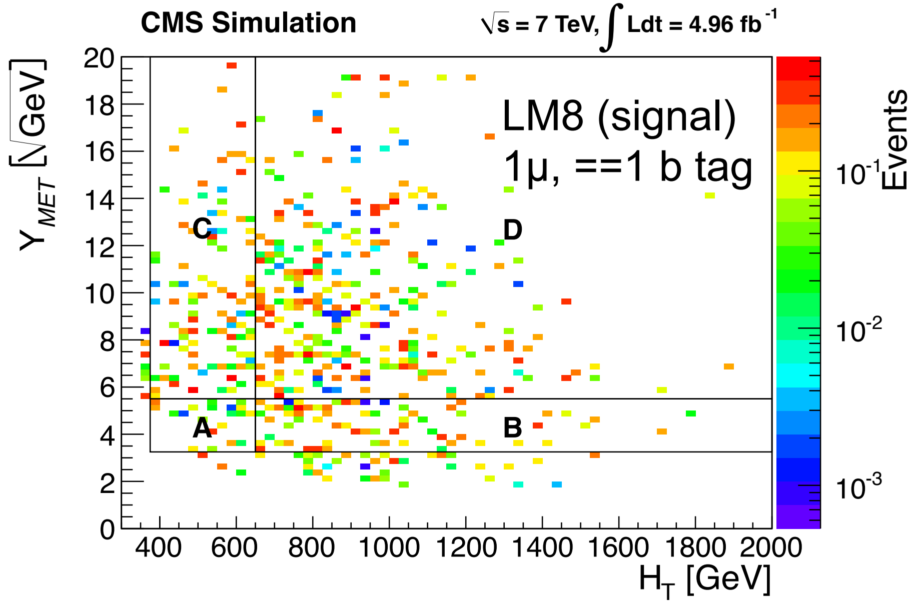
Single lepton + b: backgrounds

- All backgrounds measured together with inclusive data-driven approach
  - MET significance designed to remove correlation between HT and MET
  - If uncorrelated, can predict signal region D with

$$\hat{N}_D = \kappa N_B \frac{N_C}{N_A}$$

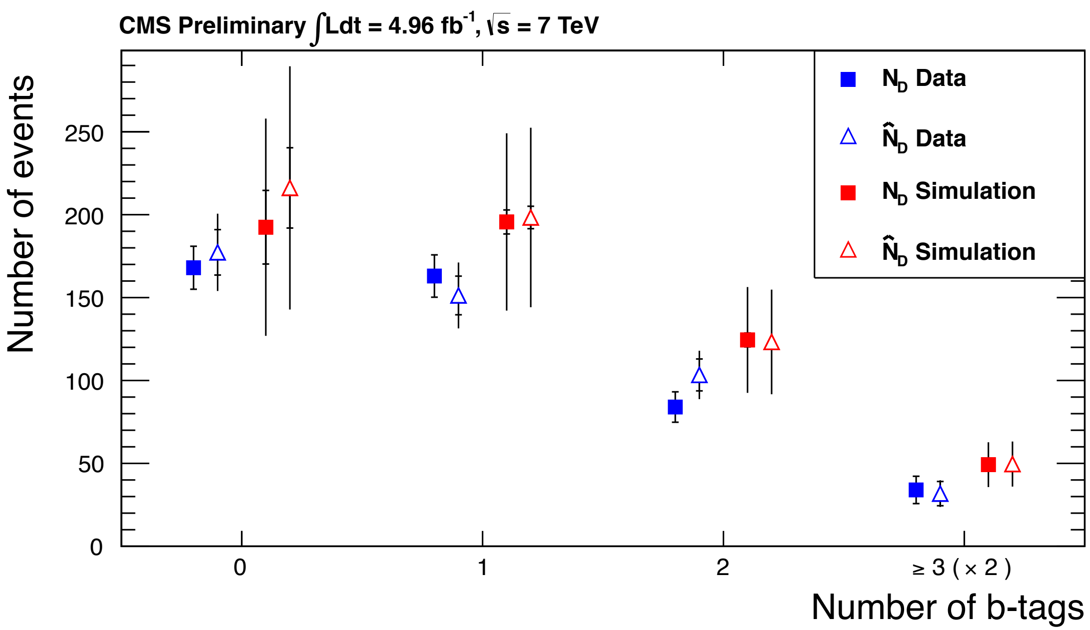
  - Kappa factors quantify effect of correlations and are measured in MC
    - κ ~ 1.2 for tt, ~1.3 for single top
  - Uncertainty on κ
    - Use 0b data sample to validate κ factor, since it has already been excluded by other SUSY searches
    - Vary proportions of different backgrounds by ±50%, stability vs HT and Y, JEC, JES, etc.





Single lepton + b: Results

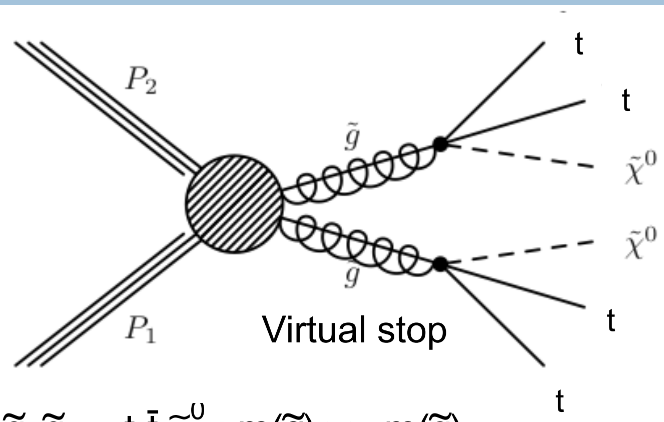
- Same kinematic selection for each nB region
  - HT > 650 GeV, Y > 5.5
- Results consistent with background predictions
- Set limits with best expected ≥ N b-tag result



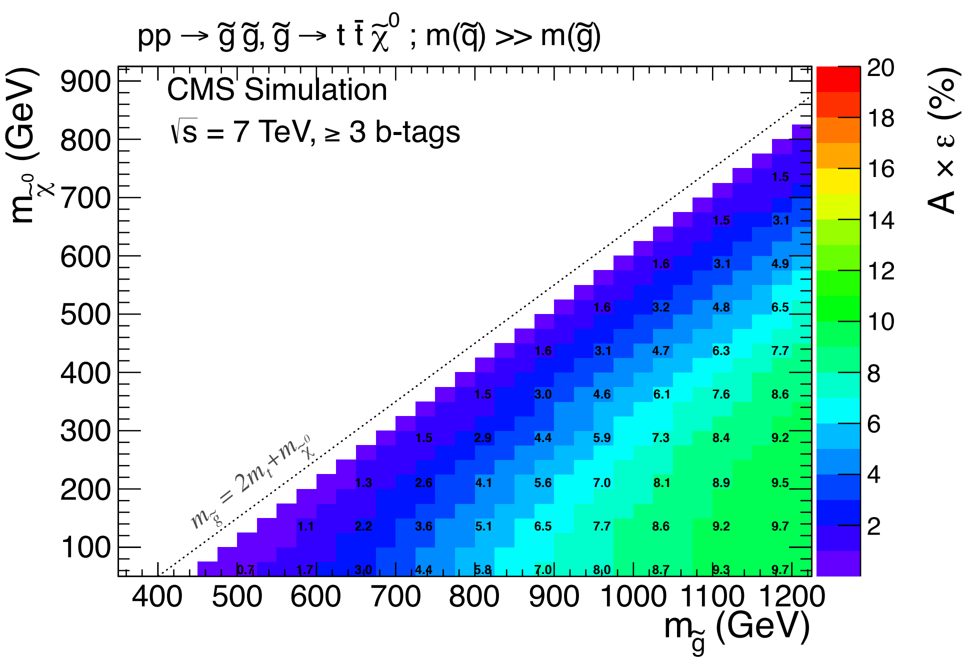
b-tags	Sample	N_D	$\hat{N}_D$
0	Σ SM	192.4 ± 22.2 ± 61.6	216.2 ± 24.2 ± 75.6
	Σ SM+LM3	295.1 ± 25.5 ± 87.6	252.7 ± 27.0 ± 83.0
	Σ SM+LM8	219.8 ± 23.3 ± 69.0	223.7 ± 24.8 ± 77.0
	Σ SM+LM13	263.4 ± 25.1 ± 79.7	248.0 ± 27.0 ± 82.7
	Data	168	177.3 ± 13.7 ± 24.9
1	Σ SM	195.6 ± 7.2 ± 53.0	198.3 ± 6.8 ± 57.6
	Σ SM+LM3	340.3 ± 9.6 ± 81.1	258.6 ± 8.3 ± 67.4
	Σ SM+LM8	257.5 ± 8.0 ± 67.3	214.4 ± 7.1 ± 60.4
	Σ SM+LM13	337.4 ± 9.4 ± 82.4	265.9 ± 8.6 ± 70.8
	Data	163	151.3 ± 11.7 ± 16.0
2	Σ SM	124.5 ± 4.2 ± 31.6	123.2 ± 3.8 ± 33.9
	Σ SM+LM3	218.9 ± 6.2 ± 47.1	165.0 ± 4.9 ± 39.6
	Σ SM+LM8	179.2 ± 5.2 ± 43.3	138.2 ± 4.1 ± 36.5
	Σ SM+LM13	242.8 ± 6.7 ± 54.1	184.2 ± 5.5 ± 45.4
	Data	84	103.4 ± 9.6 ± 10.9
≥ 3	Σ SM	24.6 ± 1.1 ± 6.7	24.8 ± 1.1 ± 7.4
	Σ SM+LM3	67.1 ± 3.4 ± 13.2	48.0 ± 2.6 ± 11.1
	Σ SM+LM8	58.9 ± 2.9 ± 13.7	35.5 ± 1.7 ± 9.3
	Σ SM+LM13	68.1 ± 3.2 ± 14.1	59.0 ± 3.3 ± 14.2
	Data	17	15.9 ± 3.7 ± 1.9
≥ 1	Σ SM	344.7 ± 8.4 ± 90.7	346.9 ± 7.8 ± 98.0
	Σ SM+LM3	626.4 ± 11.9 ± 139.7	470.2 ± 10.0 ± 115.4
	Σ SM+LM8	495.7 ± 10.0 ± 124.0	388.7 ± 8.4 ± 105.1
	Σ SM+LM13	648.3 ± 12.0 ± 149.5	505.6 ± 10.7 ± 127.6
	Data	264	272.2 ± 15.6 ± 27.9

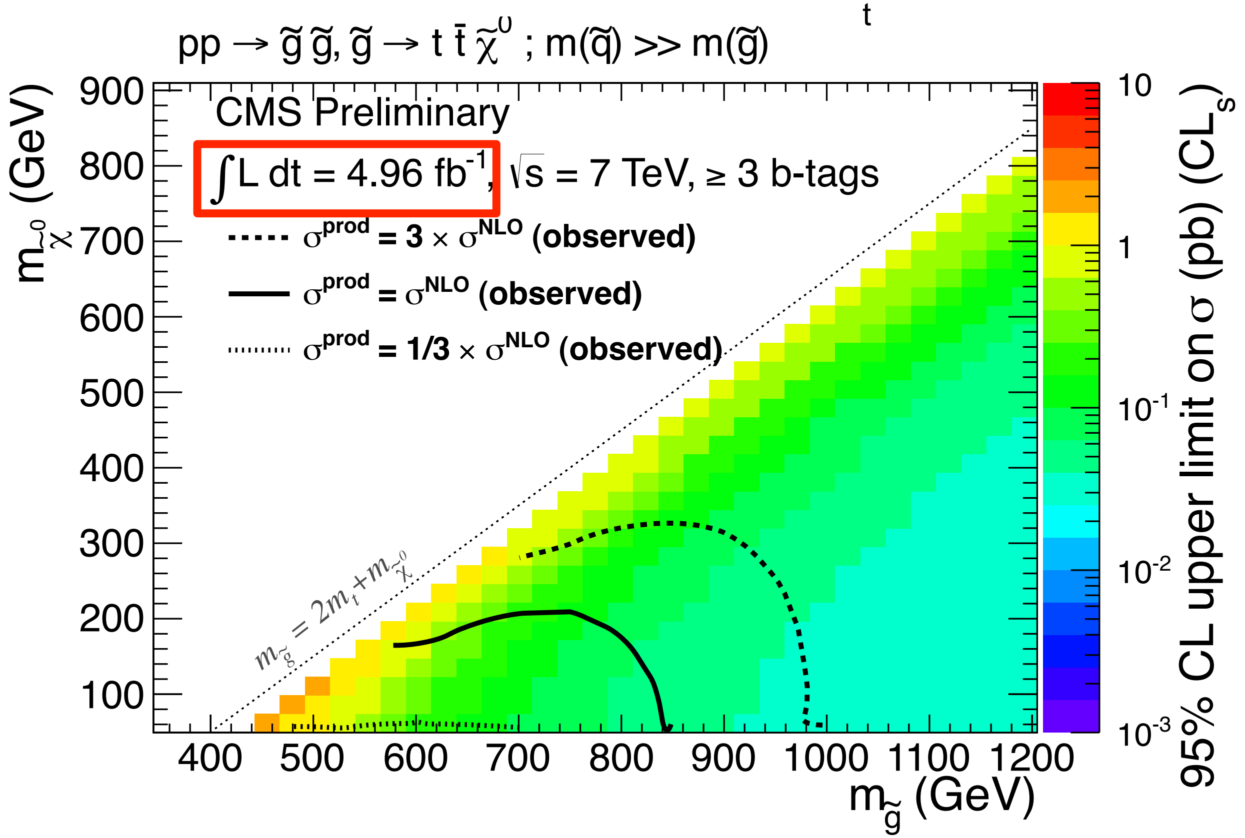
Single lepton + b: Interpretation

- Most sensitive to gluino-mediated stop production
  - Consider SMS with virtual stop
  - A×ε ~2-10% improving with larger mass splitting
  - Best expected limit from ≥ 3 b selection
- Exclude gluino mass up to ~850 GeV for m(χ 0) ~200 GeV



"T1tttt"

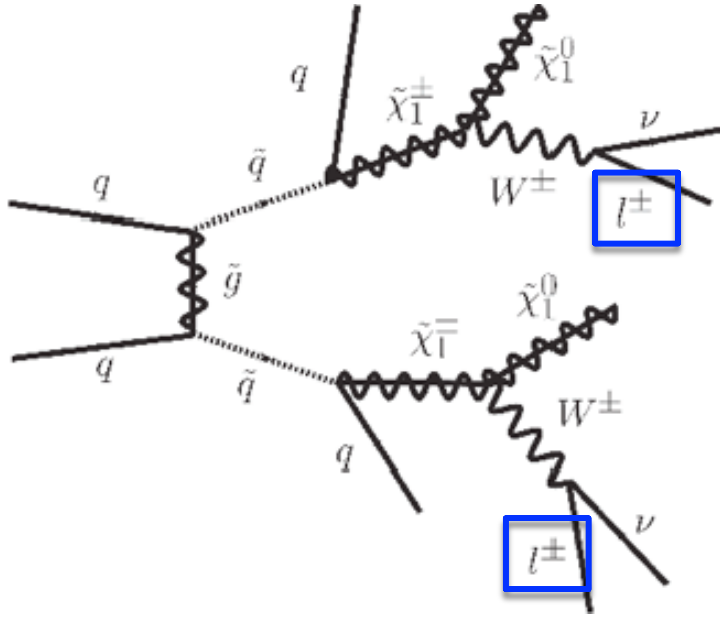


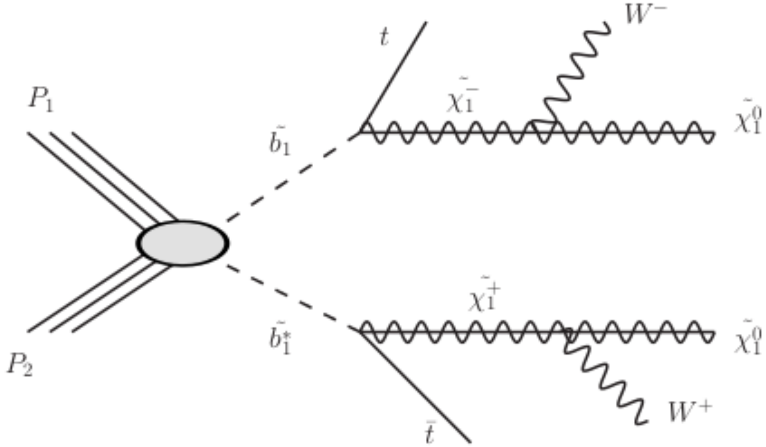


Same sign dilepton + b search

SUS-11-020

- Same-sign lepton pairs are classic SUSY searches
  - Leptons from many SUSY decay chains: chargino, neutralino, W, Z, sleptons…
  - Low SM backgrounds
- Adding b jets helps even more
  - Lower backgrounds
  - $t \rightarrow bW$ can give even more leptons
- Selection
  - $\geq$ 2 b-tagged jets with $p_T > 40$ GeV
  - Isolated same sign e or μ pair $p_T > 20$ GeV
    - M(ll) > 8 GeV to reject b's
  - Reject additional leptons consistent with Z's
  - MET > 30 GeV
    - Low cut possible with dilepton triggers

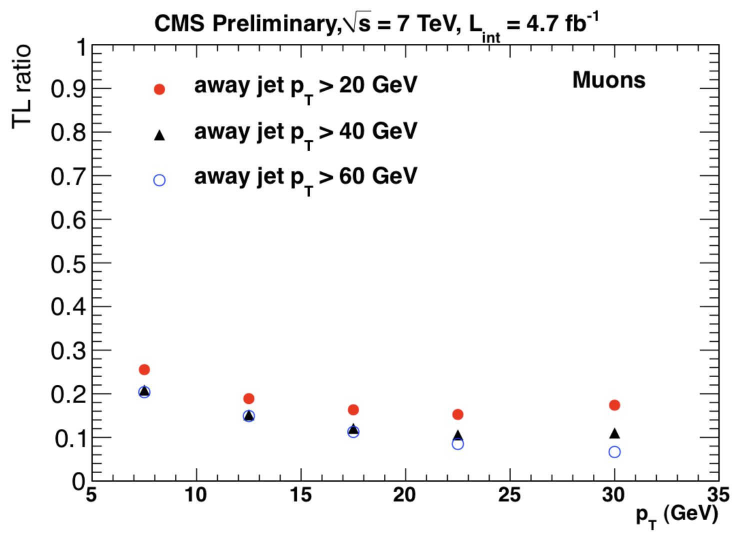


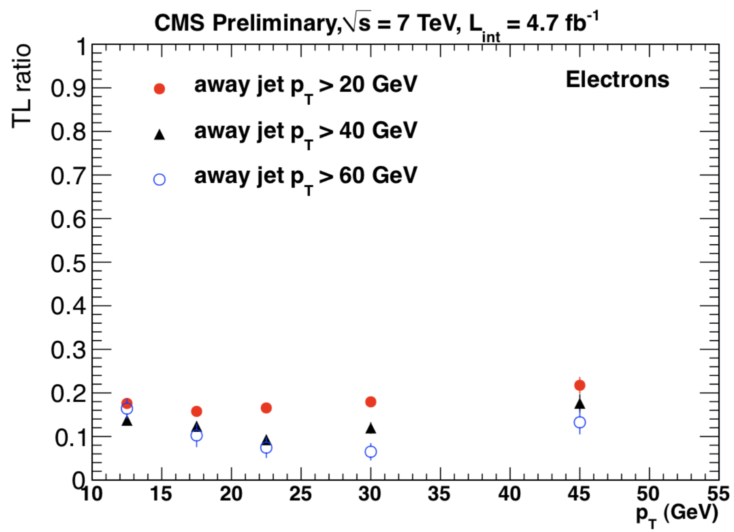


Up to 4 leptons + 2 b jets

$l^{\pm}l^{\pm}$ + b: fake lepton backgrounds

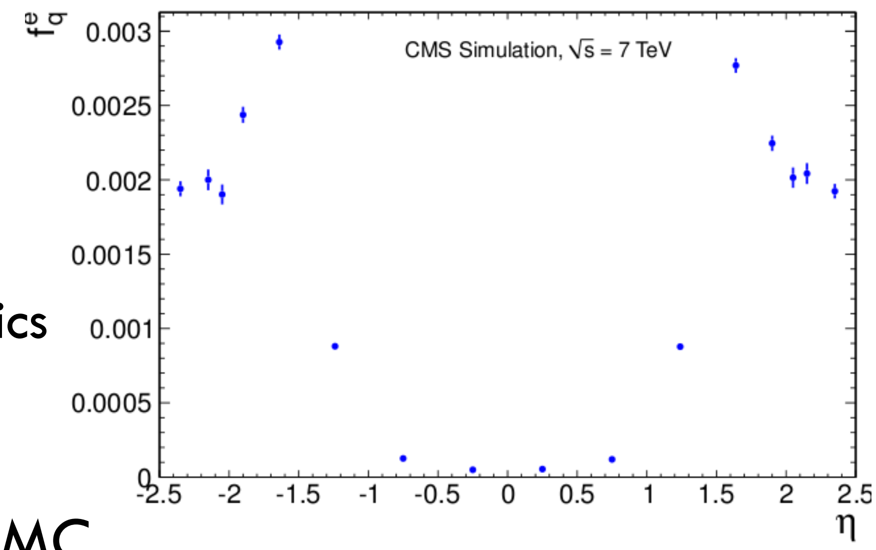
- From b,c decays, unidentified γ conversions, decay-in-flight muons, or punch through
- Use fake-dominated control sample in data of lepton candidate back-to-back with well reconstructed jet
- Loosen lepton selection and isolation requirements to measure tight/loose ratio in control sample
- Use loosened lepton selection in signal region and scale by tight/loose ratio
- Tight/loose ratio applied as function of lepton type, p_T and η

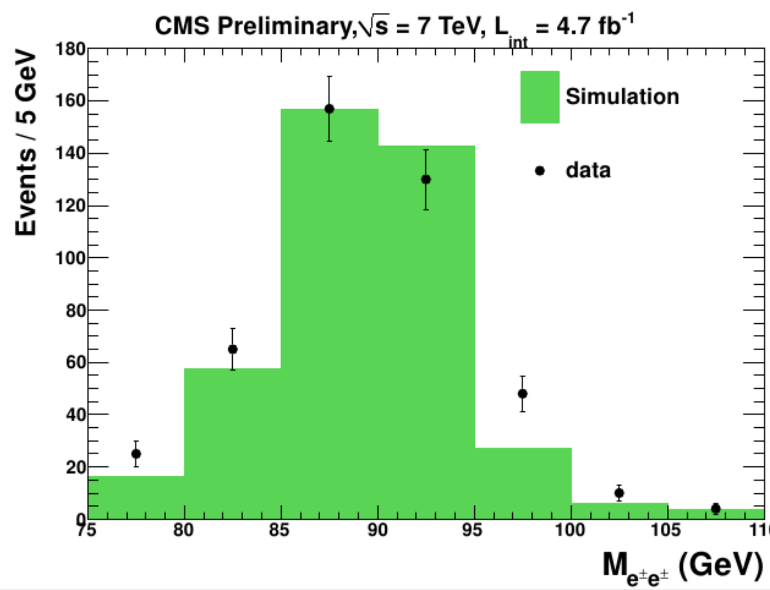




$l^{\pm}l^{\pm}$ + b: SM and q-flip backgrounds

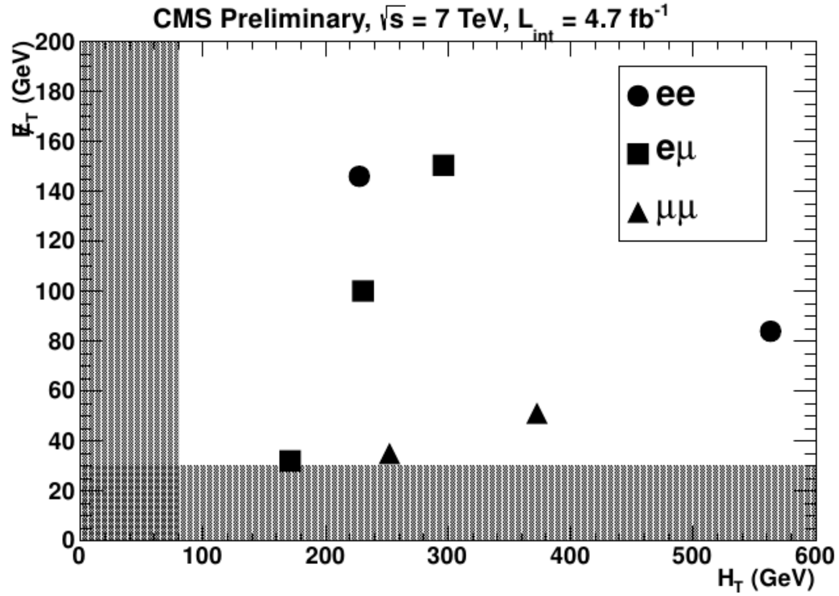
- Rare SM events with SS dileptons
  - Biggest contributions are ttW, ttZ; less from di- and tri-boson events
  - Estimated from MC
    - Will measure these SM rates when statistics allow
- Incorrect charge assignment
  - Take wrong-charge probabilities from MC
    - Negligible for muons ($\sim 10^{-5}$)
    - Important for electrons ($\sim 10^{-3}$)
      - Hard brem and conversion
      - Worst where most tracker material
    - Confirmed in data by rate of "$e^{\pm}e^{\pm}$" events peaking at Z mass
  - Background measured by counting opposite-sign events with signal selection and weighting by wrong-charge fraction





$l^{\pm}l^{\pm}$ + b: results

- 7 search regions defined with additional cuts applied
- Very low background search: 7 total events (2 ee, 2 μμ, 3 eμ)
- Good agreement between measured backgrounds and data events; no excess observed

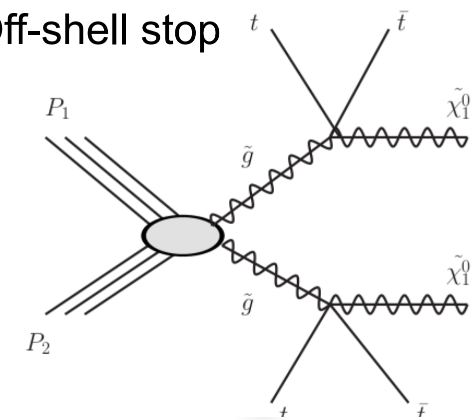


	SR1	SR2	SR3	SR4	SR5	SR6	SR7
No. of jets	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 3
No. of btags	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 3
Lepton charges	$++/--$	$++$	$++/--$	$++/--$	$++/--$	$++/--$	$++/--$
$\not{E}_T$	$\geq$ 30 GeV	$\geq$ 30 GeV	$\geq$ 120 GeV	$\geq$ 50 GeV	$\geq$ 50 GeV	$\geq$ 120 GeV	$\geq$ 50 GeV
H_T	$\geq$ 80 GeV	$\geq$ 80 GeV	$\geq$ 200 GeV	$\geq$ 200 GeV	$\geq$ 320 GeV	$\geq$ 320 GeV	$\geq$ 200 GeV
q-flip BG	1.1 ± 0.2	0.5 ± 0.1	0.05 ± 0.01	0.3 ± 0.1	0.12 ± 0.03	0.026 ± 0.009	0.008 ± 0.004
Fake BG	3.4 ± 2.0	1.8 ± 1.2	0.32 ± 0.50	1.5 ± 1.1	0.81 ± 0.78	0.15 ± 0.45	0.15 ± 0.45
Rare SM BG	3.2 ± 1.6	2.1 ± 1.1	0.56 ± 0.28	2.0 ± 1.0	1.04 ± 0.52	0.39 ± 0.20	0.11 ± 0.06
Total BG	7.7 ± 2.6	4.4 ± 1.6	0.9 ± 0.6	3.7 ± 1.5	2.0 ± 0.9	0.6 ± 0.5	0.3 ± 0.5
Event yield	7	5	2	5	2	0	0

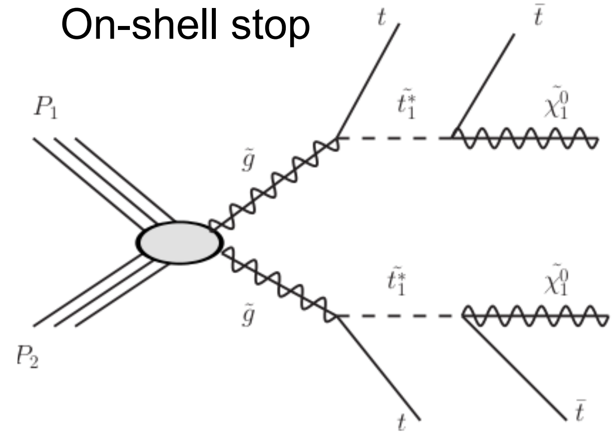
$l^{\pm}l^{\pm}$ + b: stop production limits

- Use signal region with best expected UL for each point to extract limits
  - Tightest kinematics (SR6) best most places; essentially background free
  - Looser kinematics (SR4,5) best near thresholds with low $p_T(\chi^0)$
- Exclude gluino masses below ~800 GeV in these models

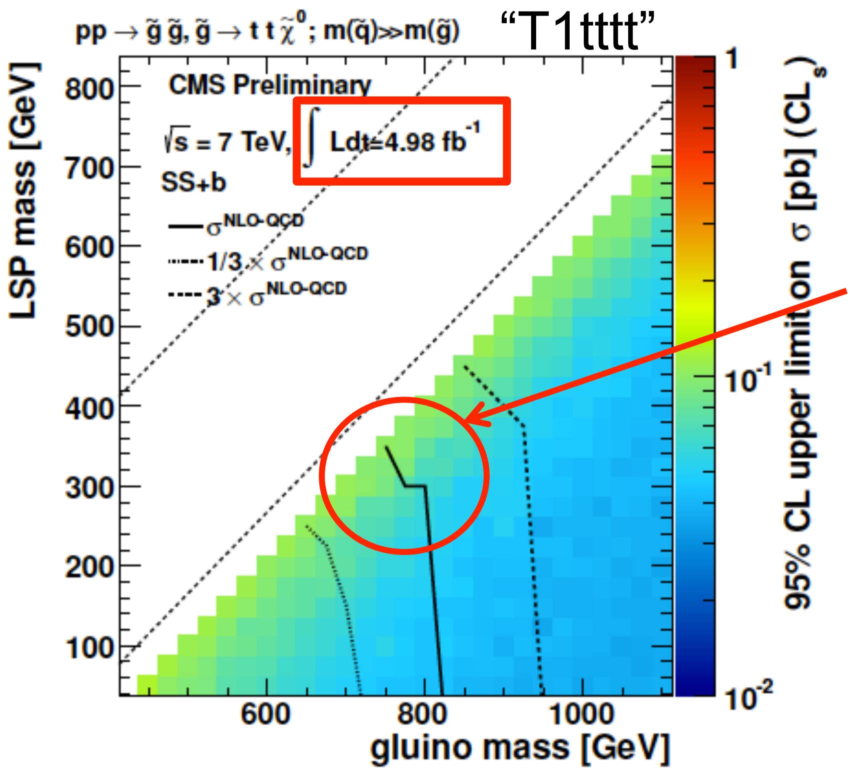
Off-shell stop



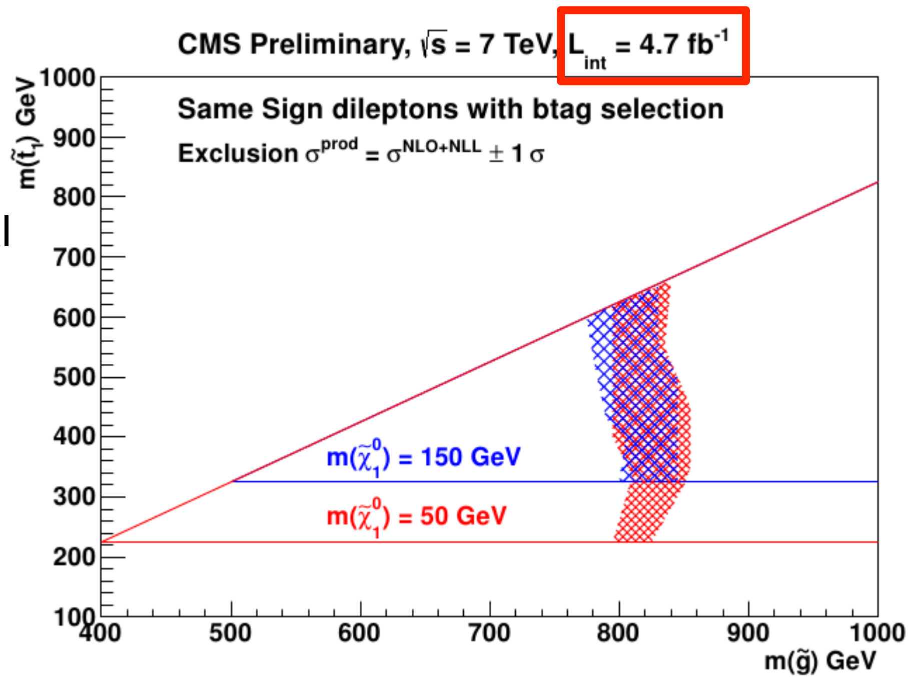
On-shell stop



$$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

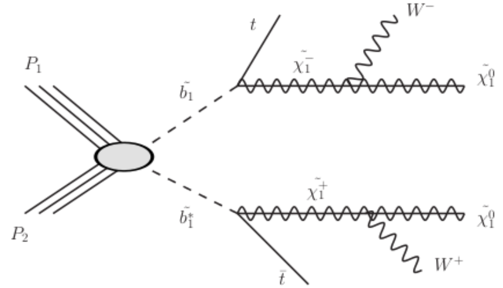


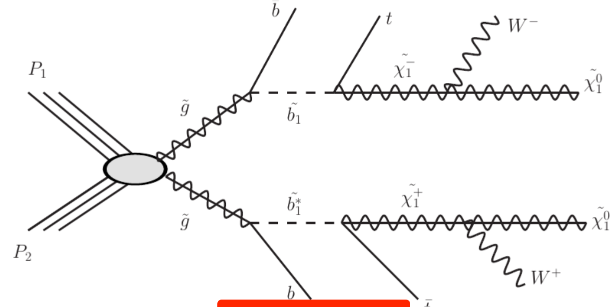
Improves over single lepton limits near diagonal due to low MET cut

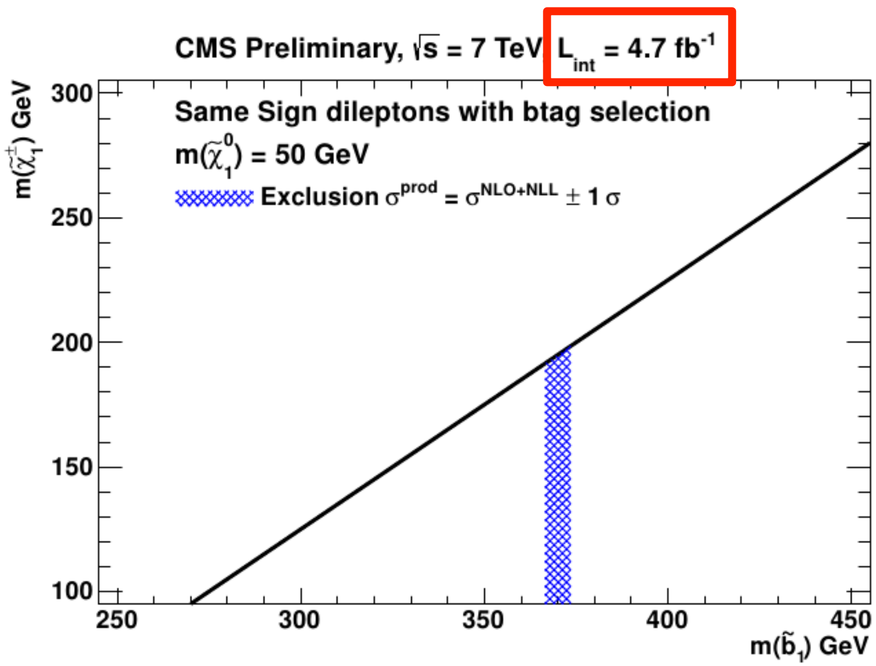


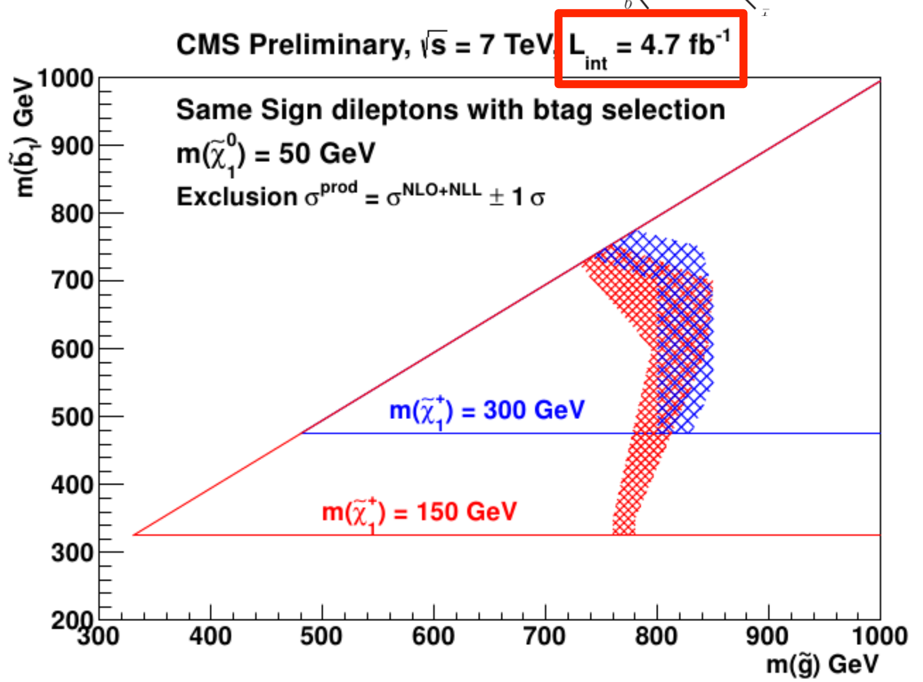
$l^{\pm}l^{\pm}$ + b: sbottom production limits

- Direct and gluino-mediated sbottom production models with SS dileptons
  - Loosest kinematic cuts (SR1,4) are best for sbottom pair production
    - Limit mostly insensitive to χ^0 mass within allowed region
    - Very sensitive to low MET signals
  - Tighter HT cuts (SR5,6) better for gluino pair production with longer SUSY decay chain with more jets
    - Exclude gluino masses below ~800 GeV





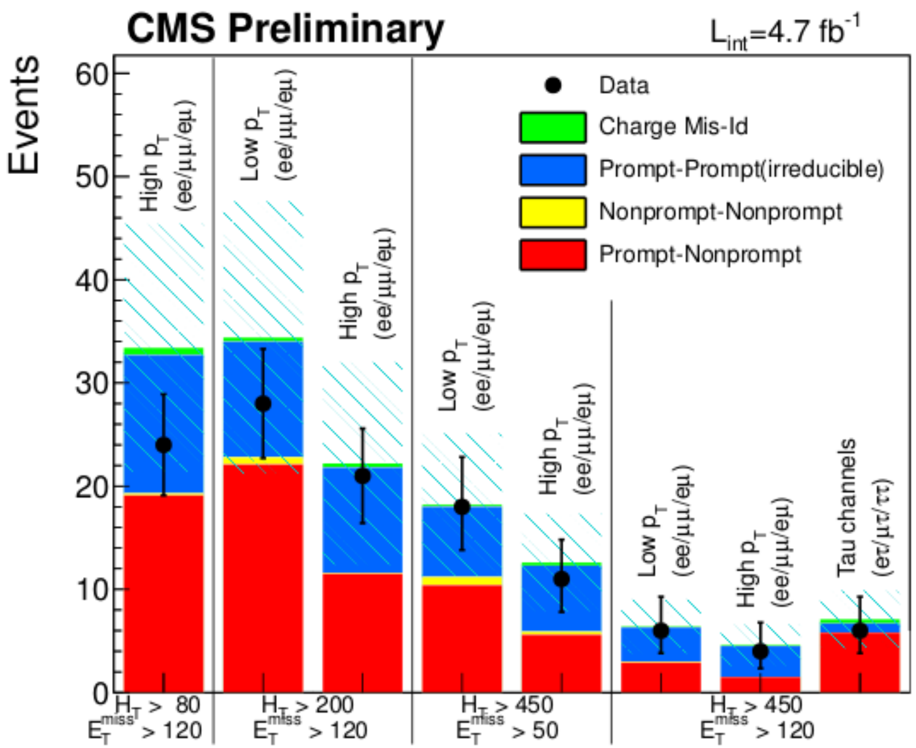


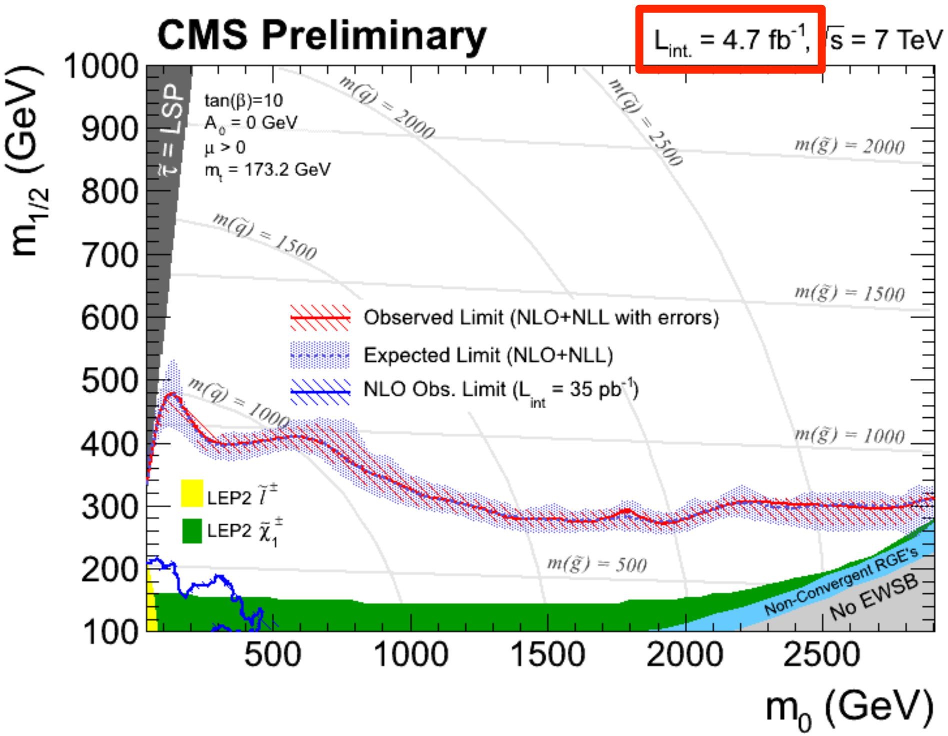


Same-sign dilepton: without b jets

SUS-11-010

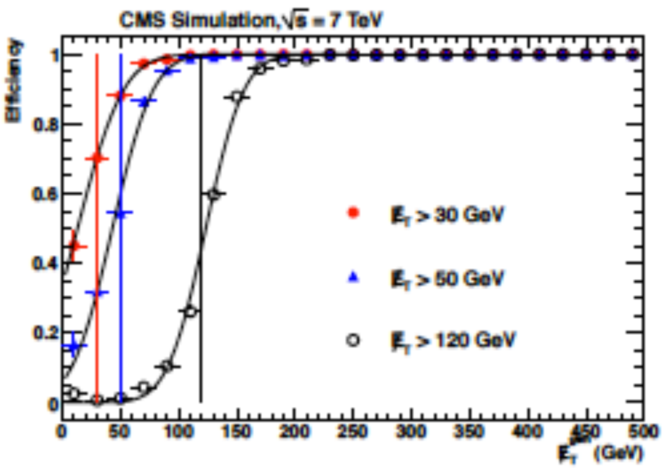
- Also update same-sign dilepton search without the b tag requirement to full 2011 dataset
  - Add low p_T lepton selection with p_T μ(e) > 5(10) GeV
  - Add hadronic τ channel with $\tau\tau$, eτ or $\mu\tau$
- No signal observed; set limits in CMSSM

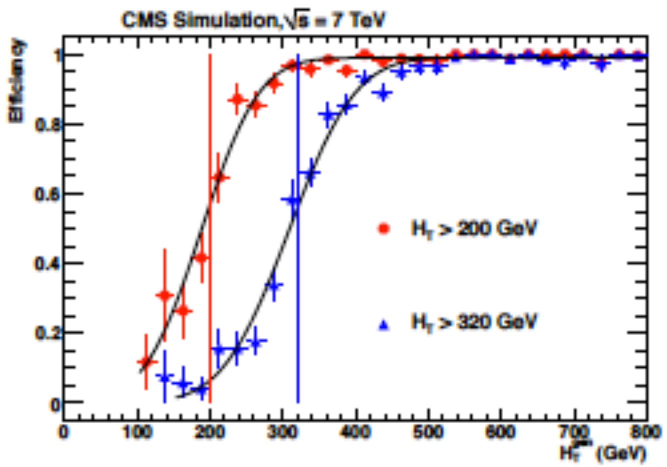




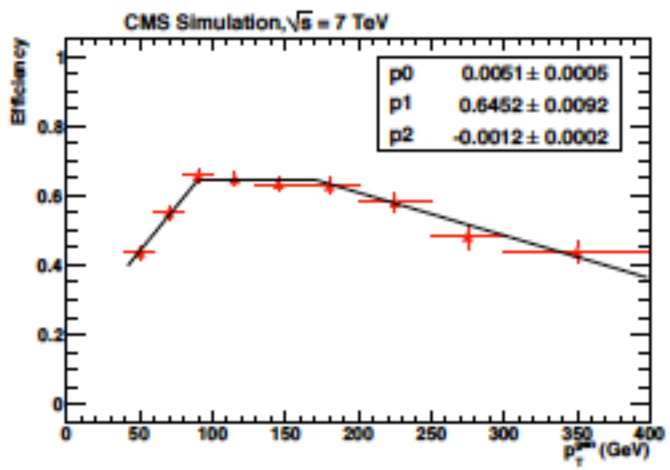
Information for model testing

- Best results only possible with full detector simulation as in previous slides
- However, many more models exist than those explicitly tested
- Results made more generally useful by providing efficiency curves for all objects as functions of generator level (hard scatter parton) kinematics
- In CMSSM no b tag result, a comparison results in limits that are within 15% of the fully simulated result





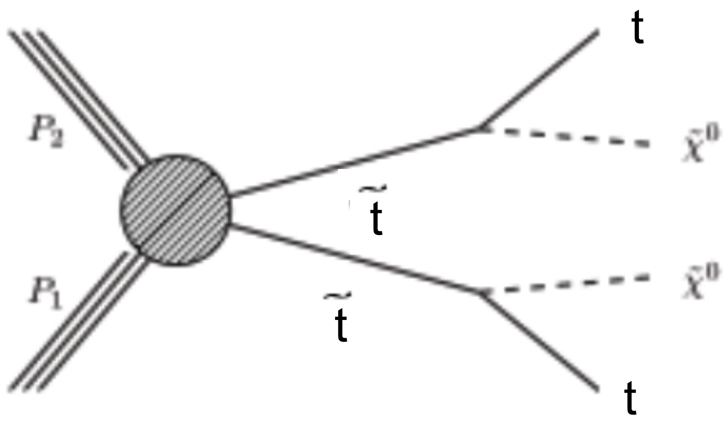
Modified generator-level definitions of MET and HT

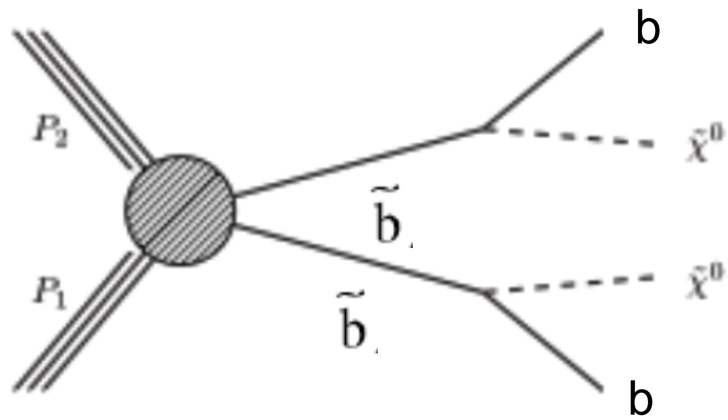


b quark p_T

In the pipeline

- Updates for everything with 5 fb^{-1} and beyond. 2012 data rolling in as we speak…
- Hadronic searches with other alternative kinematic variables also adding b jets
  - α_T, Razor
- Direct stop pair production searches
- Hadronic sbottom pair production searches





Thoughts about where to go next

- Targeted direct stop/sbottom pair production searches
  - Focus on possible signatures with split spectra—only a limited number but can be hard to get at if low MET, or too tt-like
- Continue to build better inclusive searches
  - More sophisticated use of kinematic information
    - Alternative and complimentary variables like α_T, RAZOR, M_{T2}, …
    - Squeezing all possible power with multivariate and shape-based approaches
  - Alternative and complimentary background measurements in data
    - To claim a discovery there is no substitute for data-based background measurements
    - Complementary methods to measure the same background builds confidence
    - Statistical power of multiple methods together can really pin down SM backgrounds; even regions with relatively large backgrounds could improve sensitivity
- Probing difficult phase space
  - Compressed spectra with low MET signals may require more careful triggers, relying on non-MET variables: lots of leptons, jets, b jets, photons, taus…
- Keep an open mind to look everywhere we can

Conclusions

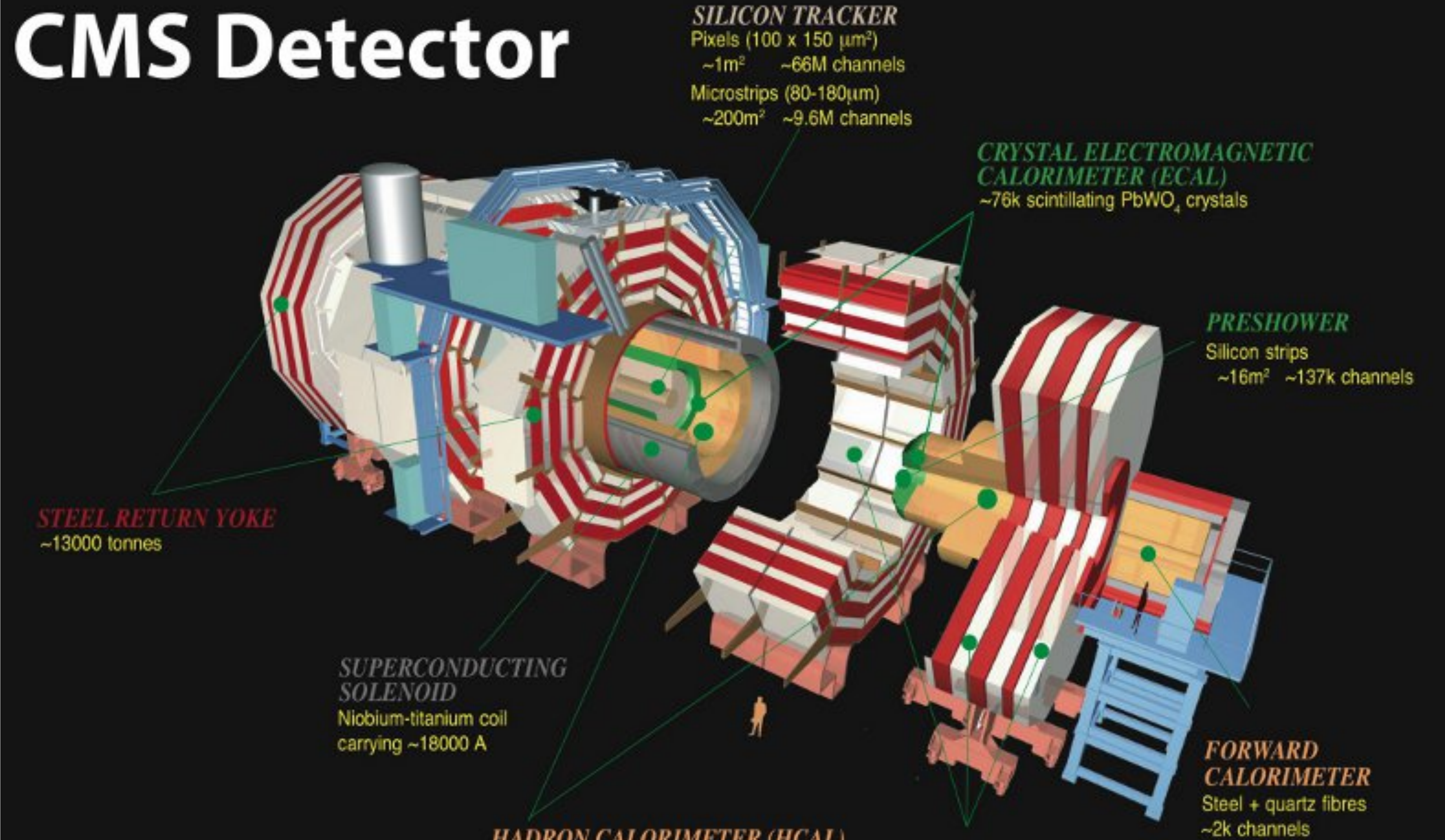
- Lots of new CMS searches with bottom jets, but still no signs of SUSY

  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

- Still lots of (natural) parameter space left to explore
- We're going to have to dig in and attack more difficult regions, but we have the machine and detectors to do it

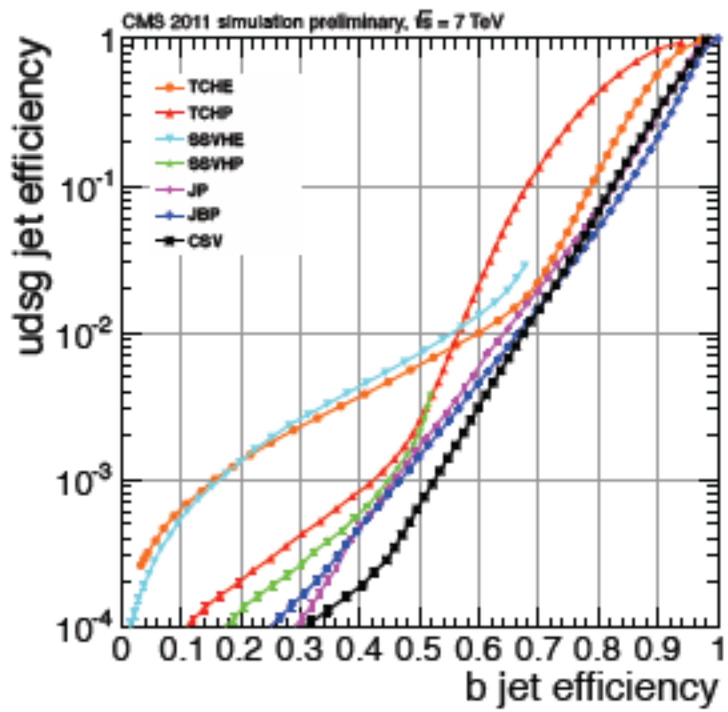
Extra slides

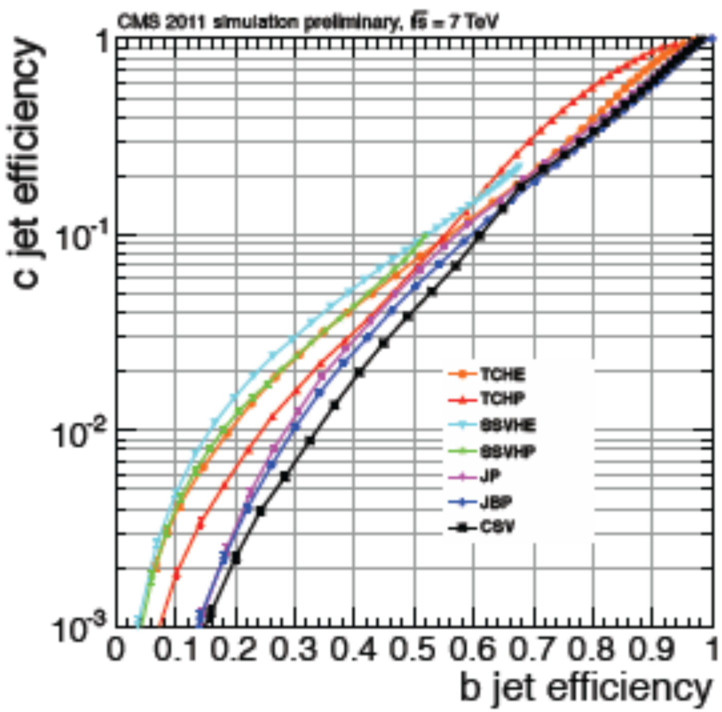
CMS Detector

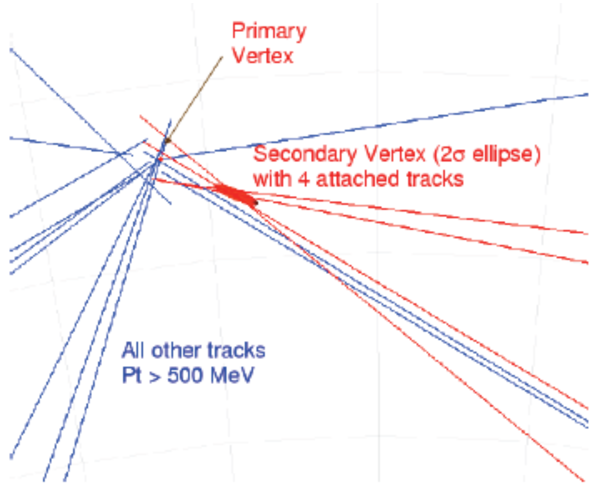


Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

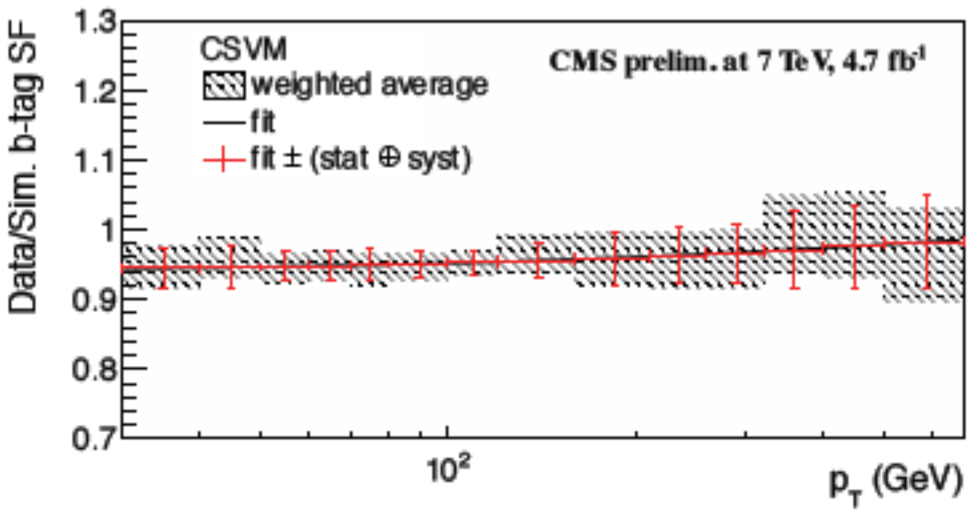
B tagging performance

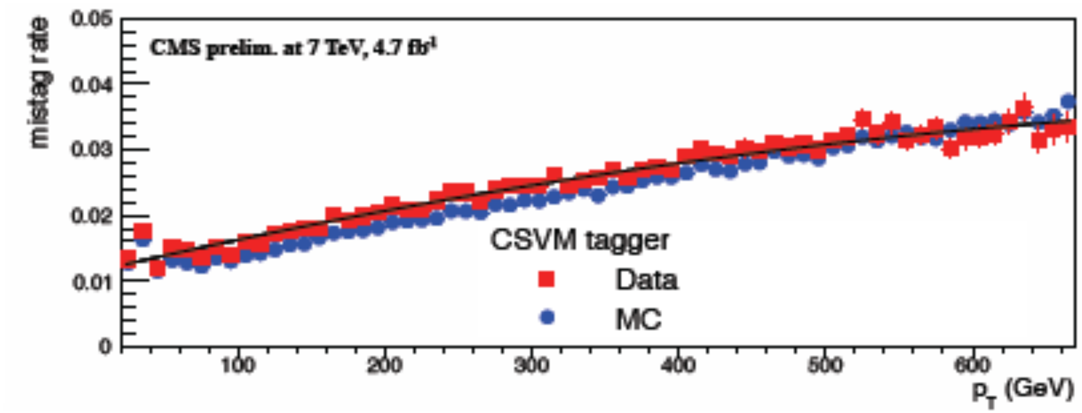




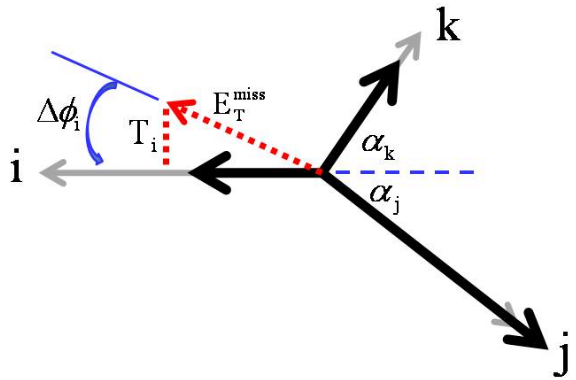


Vertex separation
2.6 mm (7σ)



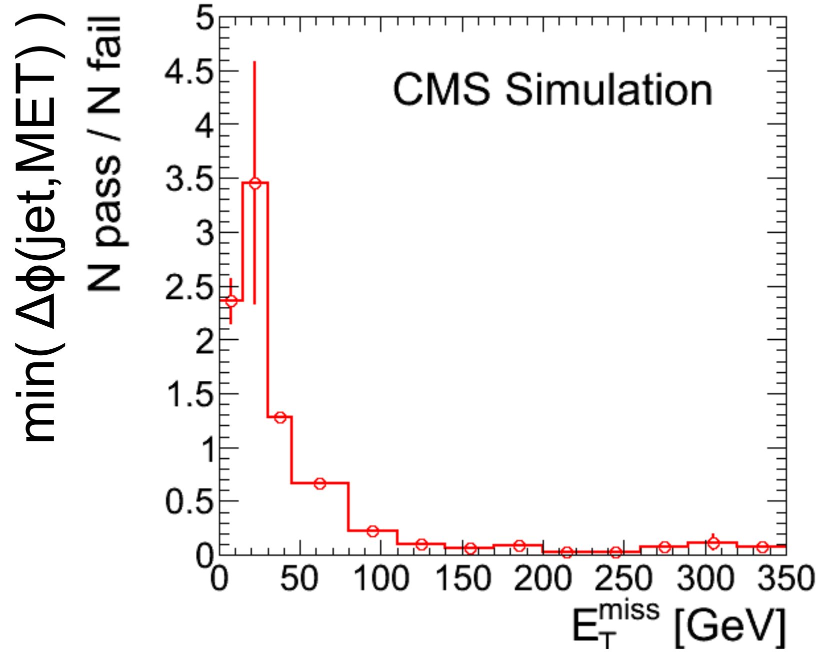


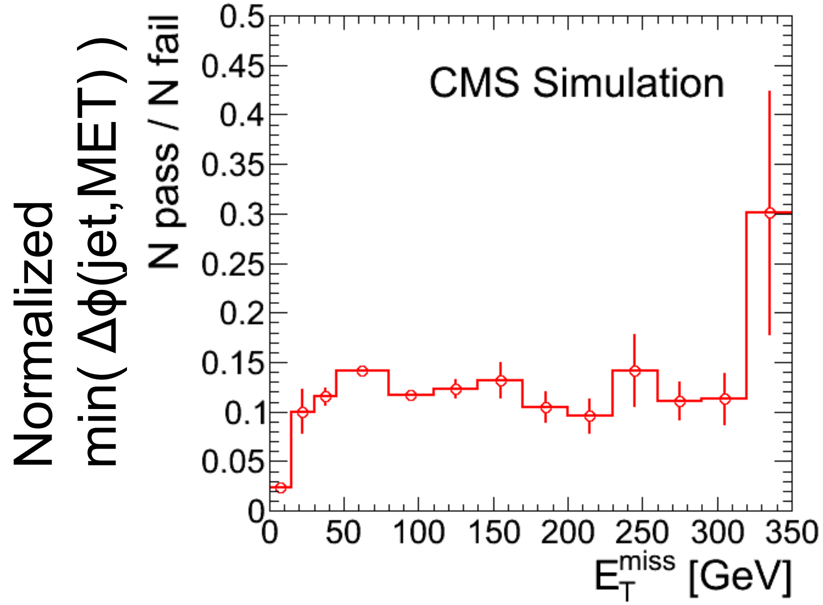
Jets+MET+b: QCD background



- Standard azimuthal separation between jets and MET is very correlated with MET
- We normalized the variable by it's resolution to remove the correlation
  - Assumes MET comes from one mismeasured $|p_T(\text{jet})|$
- Since uncorrelated can apply standard ABCD method to estimate the background in the signal region

$$N_{pass}^{HighMET} = (N_{pass}^{LowMET} / N_{fail}^{LowMET}) * N_{fail}^{HighMET}$$





MT2 definition

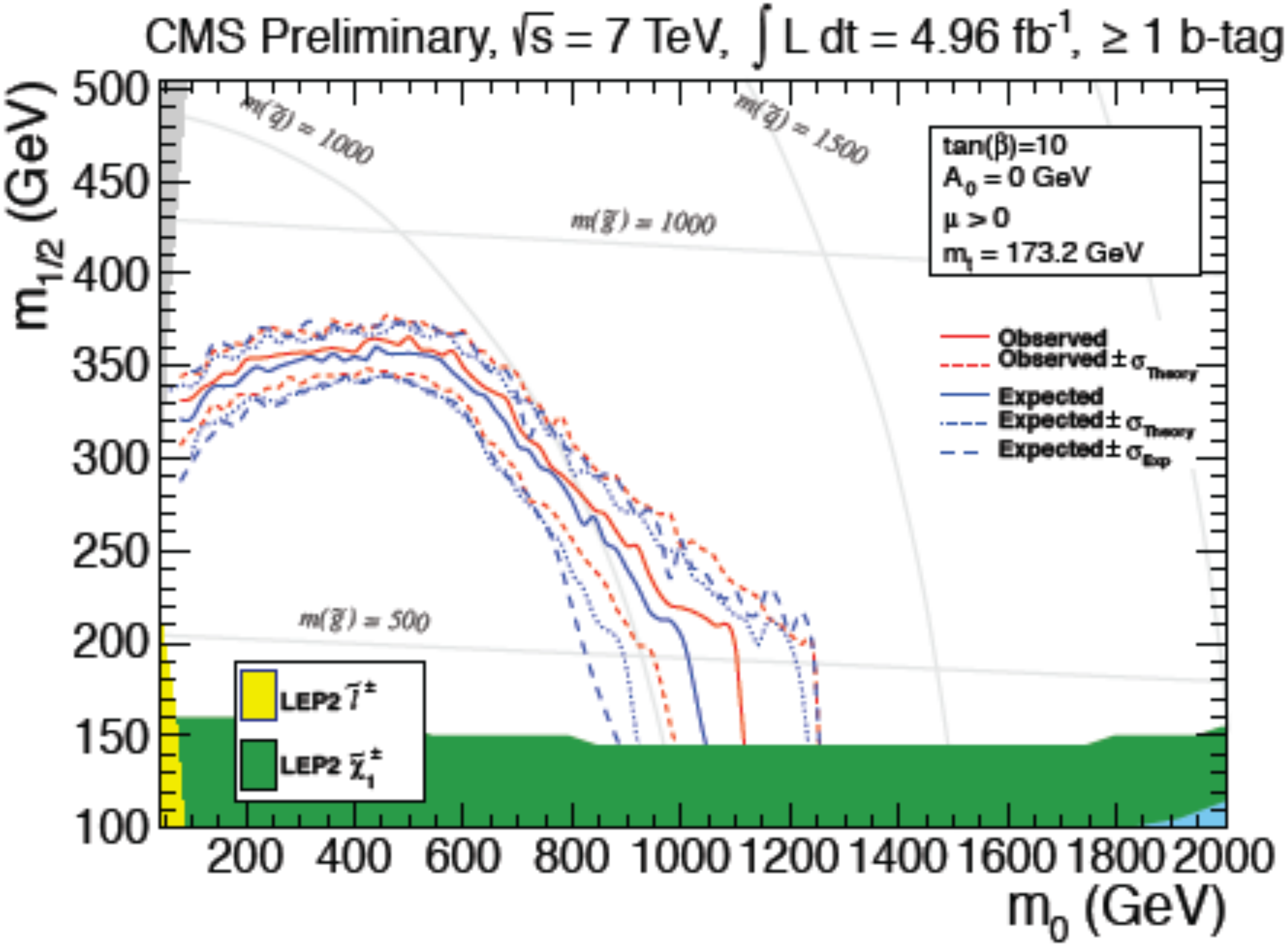
- χ = missing particle, vis = visible particle
- Keep m_χ as free parameter in general M_{T2}, set to zero in CMS searches

$$(m_T^{(i)})^2 = (m^{vis(i)})^2 + m_\chi^2 + 2\left(E_T^{vis(i)} E_T^{\chi(i)} - \vec{p}_T^{\,vis(i)} \cdot \vec{p}_T^{\,\chi(i)}\right)$$

$$M_{T2}(m_\chi) = \min_{p_T^{\chi(1)} + p_T^{\chi(2)} = p_T^{miss}} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$$

Single lepton + b: CMSSM limits

- CMSSM limits from single lepton + b search



$l^{\pm}l^{\pm}$ + b: limits on non-SUSY models

- Use $l^{+}l^{+}$ pairs only to place limits on two models with same sign decays from tt
  - Z' model with chiral couplings to uu and tt proposed to explain Tevatron top f-b asymmetry

$$\mathcal{L} = \frac{1}{2} g_W f_R \bar{u} \gamma^{\mu} (1 + \gamma^5) t Z'_{\mu} + \text{h.c.}$$

  - Maximally flavor violating model with new SU(2) scalar doublet that couples to 1st and 3rd generation quarks via $\mathcal{L} = \xi \Phi q_1 q_3$